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9 Master Thesis

6 A SIMULATION STUDY OF CHECKOUT OPERATIONS AT THE WRIGHT-PATTERSON AFB COMMISSARY.

10 Robert E./Dorough Captain, USAF
Robert H./Holliway Captain, USAF

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Customer waiting time in checkout lines at the Wright-Patterson AFB Commissary has been identified by patrons as their greatest dissatisfier. Currently a new commissary facility is under construction at Wright-Patterson. Management forecasts an approximate 25 percent increase in business; however, queue configuration and operating procedures are anticipated to remain the same. The purpose of this study was to determine if a new queue configuration for the new facility could reduce the average waiting time for customers in the checkout lines. The conclusion of this research was that a single queue configuration would reduce the average waiting times for customers

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A SIMULATION STUDY OF CHECKOUT OPERATIONS AT THE WRIGHT-PATTERSON AFB COMMISSARY

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Logistics Management

By

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and

Captain Robert H. Holliway

has been accepted by the undersigned on behalf of the faculty of the School of Systems and Logistics in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN LOGISTICS MANAGEMENT

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Thomas C. Harrington

Committee Chairman

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CHAPTER I

INTRODUCTION

Background

The history of the commissary system of the Armed Forces of the United States dates back to the Revolutionary War. The purpose of the system during that time and up until the mid-1800s was to supply America's military forces with the rations they needed for subsistence. These rations were for military members only and were frequently out of stock. Because of the shortages and the need to supply food for family members, civilian vendors, known as sutlers, opened businesses around military posts to provide these extra items. Some of these sutlers provided goods at reasonable rates; however, many others were just "get rich quick" artists who preyed upon the military.

In the late 1860s, partially to combat the sutlers and to provide support to military members in remote areas, Congress authorized the Subsistence Department, established in 1818, to allow commissaries to sell items to all military members and their dependents. In addition, the Subsistence Department began to build commissaries at installations where previously there were none or at installations having only receiving and distribution centers or coordinating offices (1:1-7; 6:16). As the number of commissaries began to increase at this time, they also began taking on the characteristics of commercial grocery stores.

Until this time, the prices of commissary items had been based solely on cost of the items. This was due to the fact that they were designed to serve military members and their families. But with the growth of the commissaries came the attitude of some members of Congress that commissaries should share a large portion of their operating expenses. In 1879, Congress passed the first legislation establishing a surcharge, which was intended to help defray the cost of operating the commissaries by covering such costs as transportation and spoilage. It amounted to ten percent of the cost of all items, except tobacco, sold in the commissaries. It only lasted a short time, however, because in 1884, Congress removed the surcharge and returned pricing to a cost basis (1:8).

It was not until the early 1950s that Congress again passed legislation relating to commissary self support. In 1952, Congressional action required that commissaries become self sustaining for transportation of goods, utilities, and the purchase and maintenance of operating equipment and supplies. Initially, a two percent surcharge was imposed; however, in 1974 it was increased to three percent. In 1976, the surcharge was raised to four percent, which remains in effect today.

The question of commissary support is still a topic of considerable debate, especially considering how commissaries have developed through the years. One of the major points to this debate is the rise in commissary sales over the years. Sales for Air Force Commissaries totaled over $1.25 billion in 1977, and they continue to show real growth, which means they are increasing above the inflation rate (7:78). Another major point is the relationship between military pay and the commissary privilege. Most military members consider the commissary privilege as an integral part of their pay, and this belief is also generally shared by Congress and the public (8:2; 16:25). A final point is the amount of savings to military consumers that commissaries offer over their commercial counterparts. Generally, the savings in Air Force commissaries has amounted to about 25 percent (7:28). If commissaries are forced into total self support, it is estimated that the total surcharge will increase to about 15 to 17 percent (8:53). A total price increase such as this would definitely reduce savings, but it is unknown as to what exact effect it would have on sales or attitudes.

Related to this is the concept of service provided by commissaries. Initially, they were designed to provide military members with the goods they needed and could not reasonably obtain elsewhere. This service is still in effect today, and is still the justification for commissaries (22:4-2). However, commissary service now entails more than just offering goods for sale; it includes areas such as store operating hours and checkout operations. Air Force Commissary Service (AFCOMS) policy is to provide the best possible service in these areas within cost and manpower limitations (5; 22:4-2).

From personal experience and from a review of literature pertaining to commissary operations, service in relation to checkout operations has been identified as a problem. Specifically, customer waiting time in checkout lines is a problem.

Problem Statement

Service in checkout operations may be an Air Force-wide commissary problem, but it has been specifically identified as a problem at the Wright-Patterson Air Force Base, Ohio commissary. This was validated by two separate master's theses conducted at the Air Force Institute of Technology (1:63; 15:23). In his 1977 thesis, Boyd used a random survey to sample active duty personnel attitudes on the value of the Wright-Patterson Commissary. In his survey, he attempted to address an aspect of the real cost of shopping for groceries not previously considered: the value of time to the customer. Since the time spent shopping at the Wright-Patterson Commissary seemed more intensive than shopping at local commercial supermarkets, he felt that it might significantly impact on commissary customer shopping habits or their perceived real cost of commissary groceries. From this survey, an element of time, the customer waiting time in checkout lines, was identified as the greatest dissatisfier among all aspects of the Wright-Patterson Commissary (1:63).

An additional factor that bears upon the problem of excessive waiting time in checkout lines is that a new commissary complex is under construction at Wright-Patterson.

Although the new complex is to be larger, with more and faster checkout registers, it is also forecast to have increased business (12:20). It is possible, though, that the increase in business could cancel out any advantage obtained through the increase in size and/or new registers. Therefore, other alternatives to reducing the waiting time needed to be evaluated so that if a possible solution was found, it could be implemented when the new commissary complex begins operations.

Research Objectives

The primary objective of this research was to determine if a new queueing system (waiting line system) could significantly reduce the average waiting time in the checkout lines for customers at the Wright-Patterson Commissary. For a thorough understanding of the problem and the research objective, several areas need to be discussed.

Scope. Many different variables interact with each other to determine how much time a customer spends in a checkout line. A list or diagram of them and their varied interrelationships could seem almost infinite and prove to be confusing to an observer. But a simple understanding of them is necessary in order to fully comprehend the problem and what alternative solutions might be possible. Therefore, the authors propose in Figure 1-1 their view of the major variables and interrelationships that affect customer waiting time in checkout lines at the Wright-Patterson Commissary. This diagram was compiled from personal experience and interviews with

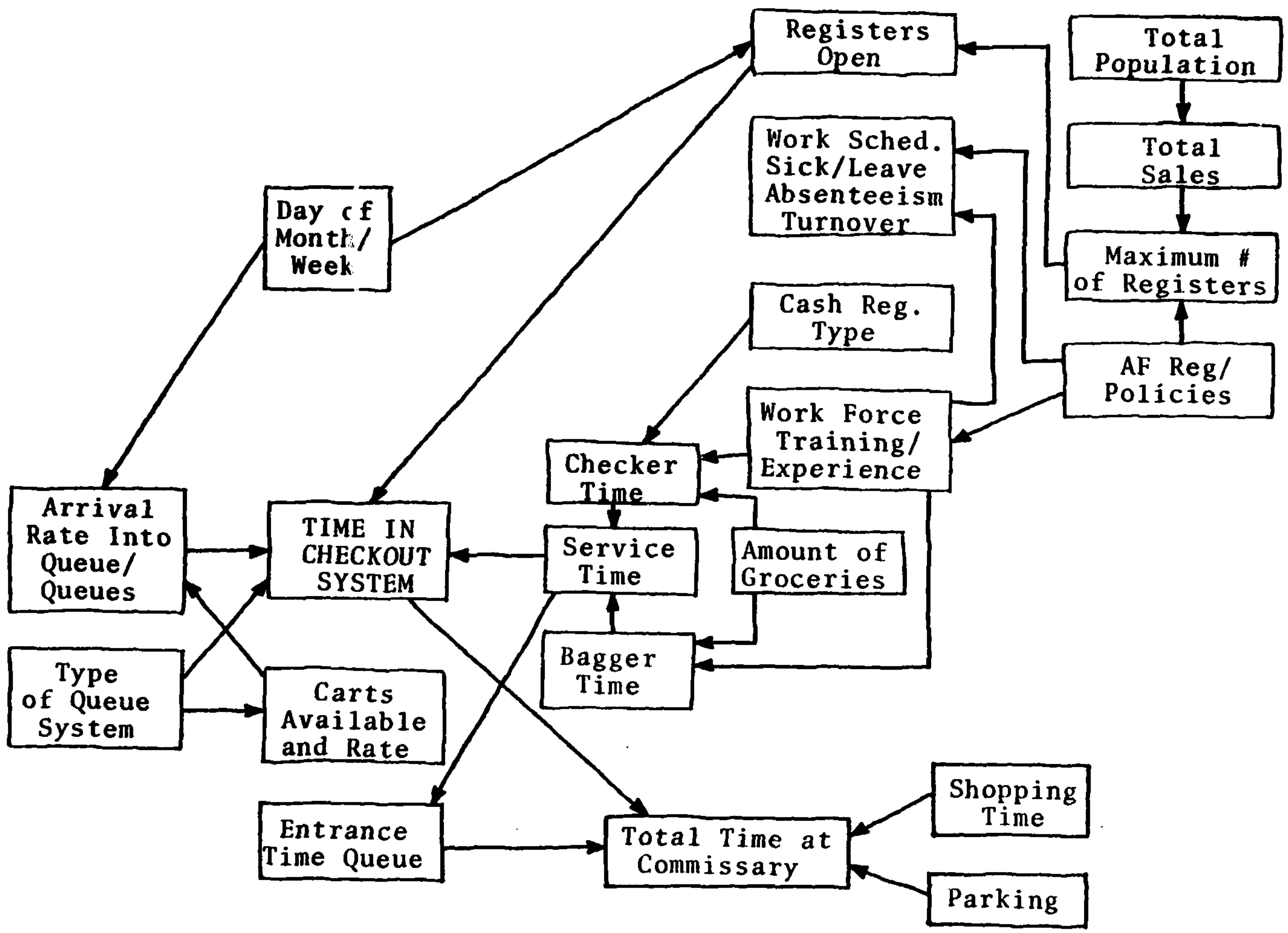


Figure 1-1

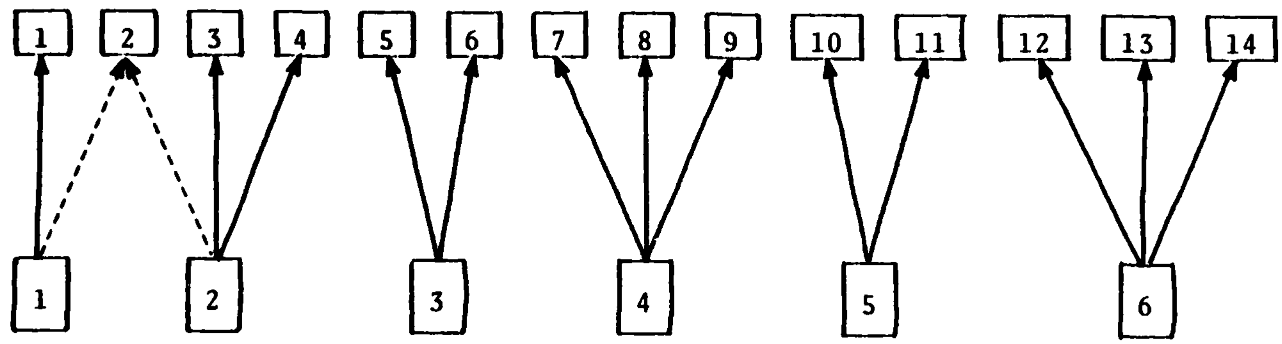
Proposed Variables and Relationships in the Commissary System the Wright-Patterson Commissary management.

As one can see from the diagram, there are many factors that determine how long a customer waits in a checkout line. The authors of this research effort focused solely on the type of queueing system to determine if a particular type of queueing system could reduce the customer waiting time in the checkout lines. The other factors could produce a significant reduction in waiting time, but they were beyond the scope of this study.

Although the problem may be typical to other Air Force commissaries, this study was limited to the Wright-Patterson Commissary for several reasons. First, the problem was specifically identified at the Wright-Patterson Commissary in prior research efforts. Additionally, the availability of data critical to the study, and the collection process for that data limited the study to Wright-Patterson. However, we believed that, even though the study was limited to the Wright-Patterson Commissary, it could possibly be adapted for other Air Force commissaries if the results proved significant.

Before a discussion of possible alternative solutions to the checkout line waiting time problem, a brief description is merited of the present commissary and of the new commissary at Wright-Patterson. The present commissary averages about $2 million in sales and 40,000 customer transactions per month (3; 11). It has a total of 14 checkout lanes (Figure 1-2). Lane 1 is designated as an express lane, where sales are limited to 12 items or less. Lane 2 alternates as either an

Checkout Lanes



Checkout Queues

Figure 1-2

Present Commissary Checkout System

express lane or regular checkout lane, depending on the demand for express service. Lanes 3 through 14 are operated only as regular checkout lanes. There are a total of six queues to the 14 registers. This configuration is due to the physical layout of the store and the use of one-way aisles. Queue 1 serves as an express line and always services register one, but also feeds register two when it is used as an express lane. Queues 2 through 6 service the remaining lanes, with each queue servicing two or three registers. Each checkout lane has one checker, who only tabulates the grocery prices, and one or more baggers, who put the groceries in sacks. The checker and bagger operate simultaneously, that is the bagger is sacking groceries while the checker is tabulating them, as opposed to operating sequentially, where the checker sacks the groceries after he/she tabulates them. The checkers presently utilize NCR Class V cash registers to tabulate the grocery bill. The present commissary has a total of 152 regular shopping carts, and it operates a total of 49 hours per week, being open Tuesday through Saturday.

The new commissary will be larger than the present commissary and will carry a larger selection of items than the present one. The average sales for the new complex are forecast to be about $2-1/2 million per month with a compatible increase in the number of customer transactions (12). The new commissary is scheduled to have a total of 17 checkout lanes (Figure 1-3). Lanes 1 and 2 are anticipated to be express lanes and lanes 3 through 17 are expected to be devoted

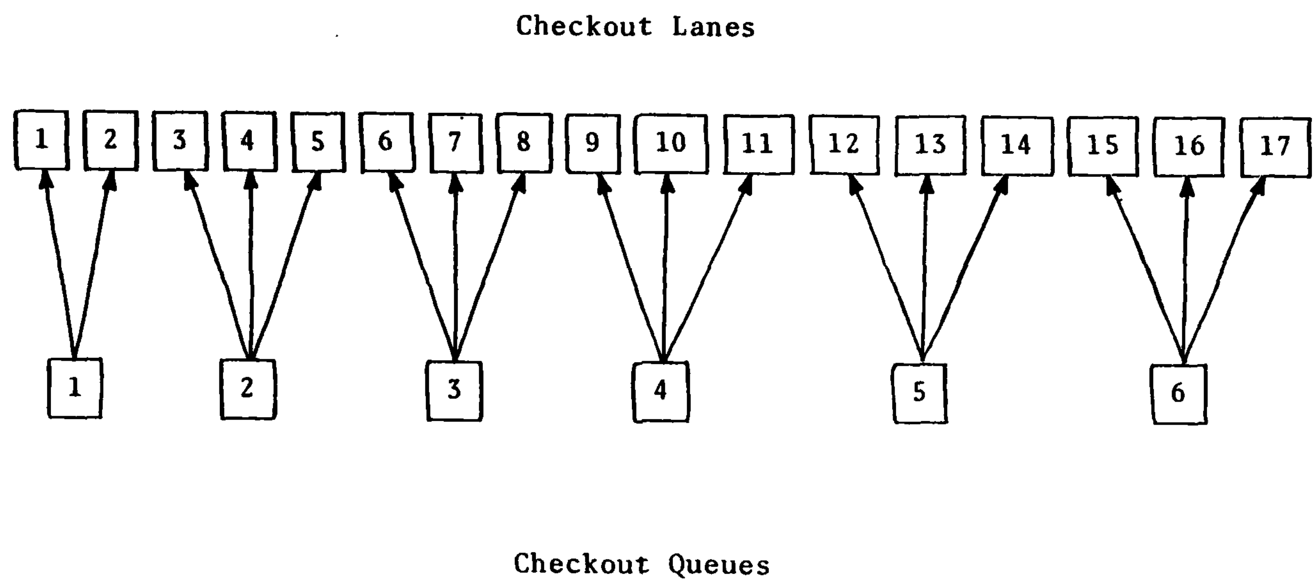


Figure 1-3

New Commissary Checkout System

solely to regular checkout operations (23). It is anticipated to have 6 queues, with queue 1 serving the express lanes and queues 2 through 6 serving checkout lanes 3 through 17, each queue serving three registers. The checker/bagger operation for the new commissary is forecast to remain simultaneous. Checkers in the new store will utilize NCR 255 cash registers to tabulate grocery bills, which is estimated to reduce checker operation time by about 5-10 percent (10:2; 18). The number of shopping carts for the new complex is predicted to increase to 200; however, the store operating times are forecast to remain unchanged.

Even though the new commissary is scheduled to have more checkout lanes with faster registers, it is yet to be determined if customer waiting time in the checkout lanes can be reduced because there are other factors, such as the anticipated increase in business, that bear upon the problem. There are several different ways that customer waiting time can be reduced, and the authors submit the following:

1) Reduce service time
    a. Increase the number of checkers and baggers
    b. Increase the speed of the checkers and baggers
        (1) Training
        (2) Faster Equipment
2) Reduce the number of customers per time period
    a. Expanding operating hours
    b. Redistribution of customer arrival times
3) Implement a more efficient queueing system

Again, we do not propose that these are the only methods available, but in our estimation, they are the most probable solutions.

Methods that reduce service time are probably some of the more valid solutions; however, there are certain restrictions and limitations to these. Increasing the number of checkers seems likely as the most probable solution; however, current plans do not call for hiring more checkers (3). Even if more checkers were hired, it might not totally solve the problem. The number of checkout lanes authorized in a commissary store is determined by HQ AFCOM/Deputy for Engineering (DE), utilizing a formula based on dollar sales per lane per hour. It was developed to provide the optimum number of checkout lanes, while remaining within service policy and cost limitation parameters (5). From this formula, the present commissary is authorized 14 checkout lanes and the new complex is authorized 17 lanes. Considering the express lanes, that gives the new complex a net increase of between two and three regular checkout lanes. If the level of business remained constant and additional checkers were utilized, the net increase would probably reduce the waiting time significantly. However, if the level of business increases as anticipated, there may not be a significant change in customer waiting time.

Increasing the speed of the checkers and baggers is another possible solution. The new store is scheduled to have new machines, the NCR 255, which are estimated to reduce checkout tabulation time by 5-10 percent (10:2). It is also anticipated that store employees will receive some training on the efficient use of the NCR 255 register. Using the "touch method" of operation, it is estimated that the NCR 255 register can reduce tabulation time by as much as 15 percent of the older NCR Class V time (19). However, there is a factor that may offset the reduction in checkout tabulation time of the new machines: the speed of the bagger. From limited observations, the authors have observed that most of the time, the service time of the combined checker/bagger operation, utilizing the NCR Class V register, is determined by the bagger. In most cases, the checker has finished tabulating the bill and completed the money exchange before the bagger had finished sacking the groceries. If this is the norm, then faster equipment combined with checker training may not affect the service time or customer waiting time.

Another possible solution to reducing customer waiting time is to reduce the number of customers. In essence, this would involve redistributing the number of customers per time period. This could be accomplished by either extending the operating hours of the store or by somehow rationing when a customer can shop. Since the commissary is currently open the maximum number of hours per week, within manpower and cost limitations, the first alternative is infeasible. Common sense would dictate the second alternative is highly unlikely, since it would be extremely difficult to design and enforce a rationing plan.

The final possible solution, submitted by the authors, is to implement a more efficient queueing system, if it can be demonstrated that another queueing system can significantly reduce the average customer waiting time. In some situations, it has been proven that a single queue to multiple servers has significantly reduced the average waiting time per customer when compared with a system of one queue for each server. For example, many banks have switched from a line at each teller's window to a common line serving all tellers. In addition to reducing the average customer waiting time, the single queue system also provides equity in the processing of customers (2: 451). A possible negative aspect of the single queue system, though, is the perceived waiting time by the customer. He may feel that he would have to spend more time in the one longer line than he would if there were several shorter lines. The authors feel that if this were encountered, customer education by the commissary would resolve this. The objective of this study was to evaluate several different queueing systems to determine if any would provide a lower average customer waiting time than the present system.

One final discussion is merited for a total understanding of the scope of this research endeavor: that is, the author's conception of the total commissary shopping queue system and their definition of the checkout queue. Figure 1-4 shows the total commissary shopping queue system. The system is a series of queues and activities. On a normal shopping trip, a person enters the parking queue and when he finds an opening, he parks his car. He then enters the shopping cart

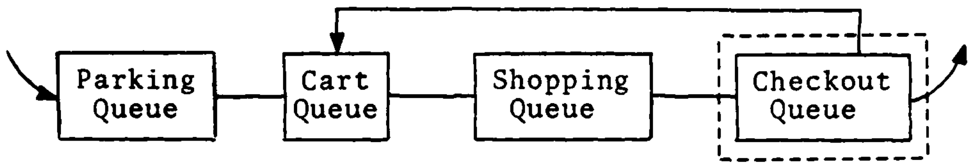


Figure 1-4

Total Commissary Shopping Queue System

queue at the store entrance and, when a cart becomes available, begins shopping. The shopping queue portrayed is a consolidation of the many queues a person encounters while selecting groceries (i.e. delicatessen service, bakery service, etc.). When he has finished shopping, he enters the checkout queue. Figure 1-5 displays the checkout queue and its components. There is a line servicing a checkout register where a clerk tabulates the grocery bill while a bagger simultaneously is sacking the groceries. For the purpose of this study, the simultaneous checking and bagging was treated as one server with one service rate. Steady state, shown in Figure 1-4, refers to the condition when all shopping carts are in use and a shopper entering the cart queue must wait for another shopper to be served in the checkout queue before he can obtain a shopping cart.

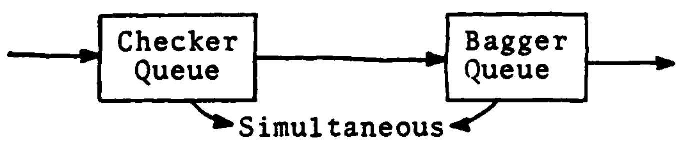


Figure 1-5

Checkout Queue

Hypotheses. Although there are many factors and combinations of factors that can affect the average customer waiting time in a checkout line, this study only researched one: the checkout queue system. We proposed to take parameters from the present commissary queue system and apply them to various proposed models of the new commissary system to determine if a new queueing system for the checkout lanes would reduce the average customer waiting time. The hypotheses for this study were:

H_0: A new checkout queue system will significantly reduce the average customer waiting time.

H_1: A new checkout queue system will not significantly reduce the average customer waiting time.

Research Question. Because this study was designed only to investigate the checkout queueing system, there was only one research question:

1. What will be the effect of different checkout queue configurations on the average customer waiting time?

Assumptions. Due to the nature of the problem and its complexities, the researchers were required to make several assumptions. The following is a list of those assumptions basic to the study.

1. The operating hours for the new store will be the same as the operating hours for the present store.

2. The forecast 25 percent increase in sales for the new store is assumed to be correct (12).

3. The corresponding forecast increase in customers

is also assumed correct (12).

4. All queue configurations tested in the experiment were assumed feasible without major physical changes to the new commissary.

Further assumptions are listed in Chapter II, and any other assumptions required during the experiment will be identified as such at that time.

Limitations. There are also several limitations that affect commissary operations and were inherent to this study. The following is a list of those limitations basic to the study.

1. The number of shopping carts available was constant at 152 for the present commissary and 200 for the new store. These figures were derived from a fire department regulation which allows only a prescribed number of people in each building (17).

2. The type of cash register for each store was set and could not change.

3. The specific day of the week or month could affect commissary operations. For example, arrival rates may increase on paydays. This factor was not explicitly considered in the initial experiment conducted under the research design of this thesis. However, the issue was indirectly accounted for by varying the arrival rate in the sensitivity analysis conducted after the initial experiment. Further, since the total commissary queue system operates at steady state most of the time (3; 16), we believe that this limitation did not significantly affect the study.

Justification

The authors believe that there are three basic justifications for this research endeavor. First, the two AFIT theses identified customer dissatisfaction with checkout operations at the Wright-Patterson Commissary. Secondly, HQ AFCOM/DE expressed interest in the study because no previous studies of this nature had been conducted, and if significant results were found, they would evaluate the possibility of implementing the solutions at other commissaries. Finally, there is a personal motivation on the authors' part to help the commissary solve this problem because it would serve all military members in the Wright-Patterson area.

Literature Review

In attempting to cover all areas pertinent to the problem of customer waiting time in commissaries, the literature review covered four major areas:

1. Commissaries in general, especially operations
2. Queueing theory in general
3. Queueing theory in relation to commercial supermarkets or other military operations
4. Queueing theory in relation to commissary operations.

Although numerous studies and other information were found, only a small amount was pertinent to this study.

In the area of commissaries in general, most of the studies dealt with the management structure of the commissary system and were not applicable to this study. However, two master's theses conducted by AFIT graduate students did provide some significant findings. They both identified problems in checkout operations at the Wright-Patterson Commissary, with one specifically identifying customer waiting time in the checkout lanes as the greatest dissatisfier to commissary patrons. However, neither study attempted to offer a solution to the problem (1:63; 15:23).

In the area of general queueing theory, there was a tremendous amount of material. The majority of it dealt with specific types of queueing models and their analytical solutions, therefore it was not directly applicable to this research. From the remainder of the material came basic queueing theory, which was the basis of this study.

A queue is defined as a waiting line of customers or units requiring service from one or more servers or service facilities. A queue will form whenever existing demand for a service exceeds the capacity of that service facility. This is not a problem as long as additional servers can be added to reduce waiting times in the queues; however, most of the time cost limitations preclude the addition of those servers. This is one of the principal reasons for the development of queueing theory, whose primary objective is the optimal balance between the cost of providing additional service and the cost of customer waiting (2:429-431).

Basic queueing theory provides a general model of the queueing process (Figure 1-6). Customers arrive from some defined source and require service from one or more service

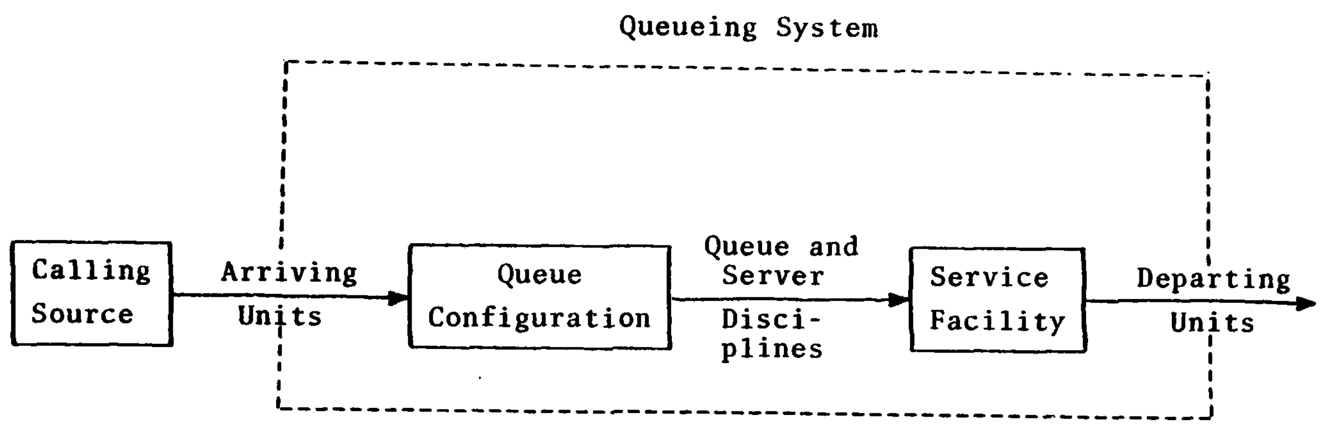


Figure 1-6

Schematic of Queue Process

facilities. If the service facility can be entered immediately, the customer is serviced and departs; otherwise he must enter a line and wait for service. Queue configuration refers to the number of available queues and their arrangement, while queue and service disciplines refer to the behavior and processing of the customers in the system. Service facilities refer to the number and arrangement of the servers (2:432).

General queueing theory has five features that are important. First, the arrival process can be from a finite or infinite population, emanate from a deterministic or probablistic generating process, or have dependent or independent arrivals. Whatever the case, it must be defined. Second, the queue configuration can have a single queue feeding a single server or multiple servers, or it can have multiple queues, each feeding a single server or multiple servers. Again, this must be specified.

The third feature, queue discipline, refers to the behavior of the customer in the queue. If the system is filled, the customer may be rejected. If the customer's estimation of waiting time is excessively large, he may balk, not enter the line, or renege, enter the line and then decide to leave. Another behavior is collusion, where several customers combine their orders for one processing. The final behavior is jockeying between queues, only evident in multiple queue systems. Each of these behaviors must be considered in the model (2:435).

Service discipline refers to behavior of the service facility. The types of service policies are:

1. First In-First Out (FIFO) - customers are served according to when they enter the queue, the earliest arrivals being served first.
2. Last In-First Out (LIFO) - customers are served according to when they enter the queue, except the last arrivals are served first.
3. Service in Random Order (SIRO) - some probablistic process is used to select a customer for service.
4. Priority Service - the selection process is determined on the basis of customer priority, either increasing or decreasing.

The specific type of service discipline must be defined for the queueing model (2:436).

The final feature, service facility, identifies the number of servers, their arrangement, and their service times. The service facility can have one or multiple servers. If there are multiple servers, they may be in series, in parallel, or both. As in the arrival process, the service time can be either deterministic or probablistic. If probablistic, the service times are generally represented by random variables, derived according to some empirical or theoretical probability distribution. For the model, each aspect of the service facility must be specified (2:437).

The number of different queue models is quite large when all the various possibilities for each of the five features is considered. Because of this, Kendall has devised a system of notation for classifying parallel server queueing models (2:438). It is: X/Y/Z, where X contains a symbol for the particular distribution of the time between arrivals, Y contains a symbol for the particular distribution of service times, and Z contains the number of servers. The following is a list of symbols and their distributions:

- M - exponential or poisson distribution, arrival or service
- D - deterministic distribution, arrival or service
- E_k - erlangian distribution of order $_k$, arrival or service
- GI - general distribution of independent arrivals
- G - general distribution of service times.

An example would be the M/M/1 queueing model, where the arrival and service rates are both described by the Poisson distribution and there is one server.

Once the model has been developed, there are two possible methods of solution: analytical or simulation. The analytical method seeks to derive mathematical expressions to find optimal values for the decision variables. Simulation, however, seeks to artificially reproduce the queueing process itself. The mathematics involved in many real world queueing problems can become very complex, therefore the analytical solution to a queueing problem may be limited. In those cases, simulation is the usual recourse (2:439). In the next chapter, this will be explained in further detail.

The third area of the literature review consisted of a search for material about queueing theory in relation to commercial supermarkets or other military operations. The material uncovered relating to commercial supermarkets was not applicable to this study since commercial operations are distinctly different from commissary operations (i.e. volume of business) and have different operating procedures. As for other military operations, only one study was found. It dealt with queues for pharmacy operations at an Air Force hospital, and since there was only one server, it also proved to be of little value to us.

The last area, queueing in relation to commissaries, revealed that no published studies had been conducted in this area. This was confirmed by interviews with HQ AFCOM/DE personnel (5). Since there were no previous studies in this area and the problem had been identified, it is hoped that this study can provide some information to fill the void.

Plan of the Report

Chapter I has provided an introduction to the research with the background, problem, objectives, justification, and literature review for the study. Chapter II will provide the methodology for how the research was conducted. Chapter III will detail how the data were collected, what data were collected, and an analysis of the data. Chapter IV will provide the computer model formulation and manipulation, to include verification and validation. Chapter V will conclude the study with the model results and the conclusions and recommendations for the study.

CHAPTER II

METHODOLOGY

Overview

As stated in Chapter I, we used queueing theory as the method by which we attempted to reduce the waiting time in the checkout system of the Wright-Patterson Commissary. The specific technique that was used to apply the queueing concepts was simulation. "The primary motivation for simulating a queueing system is the inability to generate meaningful analytic solutions for complex queueing structures [2:498]." Some of the complexities which can motivate the simulation of any queueing system as opposed to analytical solutions are stochastic arrival and service rates, breakdowns in service facilities, and a variable number of service facilities open at any particular time. These complexities inhibit the use of analytical solutions because analytical techniques are restricted to a limited class of theoretical distributions for describing the arrival and service rates and assume deterministic service facility configurations. Since the commissary is a dynamic system, with conditions always changing, the authors believed that simulation was the most appropriate method by which to find a solution to the problem of waiting time in the checkout system of the commissary system.

Modeling and Simulation

There are numerous definitions of simulation, but in general, it is a method that allows experimentation on a model of the real system. In this project, the real system under study was the checkout system at the commissary. "Simulation is primarily concerned with experimentally predicting the behavior of a real system for the purpose of designing the system or modifying behavior [2:476]." System design is the key point for the purpose of this project. It was hoped that the results of this project could contribute to the design of checkout activities at the new facility when it opens. Another definition of simulation served to focus the purpose of this research:

> Simulation is the process of designing a model of a real system and conducting experiments with this model for the purpose either for understanding the behavior of the system or of evaluating various strategies for the operation of the system [20:2].

Our purpose was to evaluate the different queue configuration strategies which could possibly be implemented at the new commissary.

The results of a simulation do not provide a "solution" to the problem under study as do analytical techniques. Rather, they provide a tool that decision-makers can use in analyzing complex systems. With this in mind, the use of simulation can provide numerous advantages for the decision-maker. While there are many advantages, four of them are of importance to this project. The first advantage is that direct experimentation (changing queue configuration) on the real system, the present commissary, could greatly disrupt operations. Simulation, however, does not require experimentation on the real system. A second advantage is that simulation allows the exploration of many alternative strategies, whereas the real system may not allow it. In this project, direct experimentation and exploration of alternative strategies on the real system (new commissary) was impossible because the facility is not open yet. As stated earlier, another advantage of simulation is that it can be used when mathematical problem formulations/analytical techniques do not exist. Numerous queueing models are in this category. A final advantage is that simulation allows for the compression of time and the researcher has control over the time element (20:11).

As with any method or technique, there are also disadvantages which must be kept in mind when performing a simulation. The first disadvantage is that a simulation can appear to accurately reflect the real system when, in fact, it does not. Another disadvantage is that simulation is not a precise science, and it is difficult to measure the imprecision. Sensitivity analysis can only partially overcome the imprecision (20:73). Therefore, even though there are disadvantages to simulation, we concluded it was the best method by which we could accomplish our objectives. "Thus, as with other arts, it is not so much the technique that determines success or failure, but rather how the technique is used [20:14]."

The simulation process can be thought of as involving nine steps. These steps are listed here with a brief description and will be covered in greater detail later in the chapter, although certain steps will be combined.

1. System Definition - Determining the boundaries, restrictions, and measures of effectiveness to be used in defining the system to be studied.
2. Model Formulation - Reduction or abstraction of the real system to a logic flow diagram.
3. Data Preparation - Identification of the data needed by the model and their reduction to an appropriate form.
4. Model Translation - Description of the model in a language acceptable to the computer to be used.
5. Validation - Increasing to an acceptable level the confidence that an inference drawn from the model about the real system will be correct.
6. Strategic Planning - Design of an experiment that will yield the desired information.
7. Tactical Planning - Determination of how each of the test runs specified in the experimental design is to be executed.
8. Experimentation - Execution of the simulation to generate the desired data and to perform sensitivity analysis.
9. Interpretation - Drawing inferences from the data generated by the simulation [20:23].

Although the steps are listed in a sequential order for ease of understanding, the process is more of an interactive process whereby all steps are accomplished, but the order is determined to a great degree by the system under study and the conditions surrounding the research itself. For example, the identification and reduction of the needed input data is affected by the choice of the computer language, and the experimental design is also dependent to some degree upon the computer languages which are available.

System Definition

The system definition phase of the simulation was covered in Chapter I. Again, we looked only at the checkout system of the entire commissary system. "All systems are themselves subsystems of other larger systems. Therefore, we must specify the purpose and restrictions under which we create our abstraction or formal model [20:26]." Realizing that the checkout system is affected by many factors, the decision was made to limit the scope and to model only the checkout system. The purpose was to reduce the waiting time in the checkout system only through the evaluation of different queue strategies. If the system under study is defined, the environment of the system must also be defined.

> Each system has something internal and external to it. What is external can pertain but to its environment and not to the system itself. However, the environment of a system includes not only that which lies outside the system's complete control but that which at the same time also determines in some way the system's performance [18:39].

For this study, the environment was considered to be those activities which take place before the customer arrives to the checkout queue and after the customer leaves the service facility. Even so, many of the other factors which are considered to be in the environment of the checkout system were implicitly considered in our system. For example, employee training and experience are reflected indirectly in the service time of the cashier/bagger. Another example is that the cart queue can affect the arrival time, but this was indirectly accounted for in the determination of an arrival rate distribution. Therefore, the checkout system can be considered as an entity in and of itself, with the realization that it is affected by many factors in the environment.

One restriction of our system definition was that we did not consider the express queue line at the commissary. It is definitely a part of the real system, but the authors did not believe the waiting time in the express line was as great a problem, since the customer is restricted in the number of items that can be purchased, thereby reducing service time.

Model Formulation

The second step in the simulation process is the model formulation. In one sense, the model formulation was accomplished in Chapter I and in the previous section on system definition.

> A model is a representation of an object, system or idea in some form other than that of an entity itself. Its purpose is usually to aid us in explaining, understanding, or improving a system [20:4].

The diagrams presented in Chapter I are pictorial models of the various systems as we see them. "As an aid to communication, well thought out models have no peer. 'One picture is worth a thousand words' testifies to this function [20:6]." The model formulation helps to focus on the factors which are important to the system being studied and these factors are input to the simulation, which is itself a model of the real situation.

> When attempting to build a model, we could include an infinite number of facts and spend an endless amount of time gathering detailed facts about any situation and defining the relationships among them. Consequently, we must ignore most of the actual features of an event under study and abstract from the real situation only those aspects that make up an idealized version of the real event [20:17].

Thus, it can be seen that system definition and model formulation are very closely related. Our definition of the system affected the model we formulated. We experimented on an idealized version (model) of the system as opposed to the real system. The model of the checkout system which we experimented on was composed of certain components.

> By components, we mean the constituent parts that when taken together make up the system. The system is designed as a group or set of objects unified by some form of regular interaction or interdependence to perform a specific function [20:15].

In our model, we had customers arriving to the first in-first out checkout queue/queues, waiting in line until they could be served, being served by the cashier and bagger, and departing the system. For this model, certain assumptions were made. The first assumption was that no balking was allowed. Balking is when a customer arrives, views the queue line, and leaves the system. The second assumption was that there was no reneging, which is when a customer gets in the queue line, waits for awhile, and then decides to leave. It was estimated that there are two to three balks/reneges per day in the present commissary (17). We, therefore, believed that this was not significant for our model. Another assumption was that there was no collusion. This is where several customers band together and one customer waits in line and purchases not only his items, but items for the other people. Common sense would indicate that this was a valid assumption. A final assumption was that there was no jockeying, switching lines, because the layout of the aisles prevents a customer in one queue from seeing another queue. With this model in mind, certain data were collected to run the simulations.

Data Requirements for the Model

The first inputs for the model can be classified as variables, which can further be broken down into independent and dependent (response) variables (9:95). The number of queues in the present and new commissary is an independent variable. The present store has five queues (excluding the express queue). The queue configuration for the new store has not been determined, but it was estimated that the configuration would be similar to the present store (17; 23). Our model evaluated one, two, three, and five-line queue configurations for the new facility. These configurations were selected for evaluation because we concluded that they were the most feasible based upon our examination of the layout design of the new commissary. The specific queue configuration determines, in part, the only response variable of interest in this study, which is customer waiting time.

The second set of specifications or inputs to the model are classified as parameters. "Statistical analysis often involves attempts to determine these unknown but fixed parameters for a set of data [20:15]." For this study, there were four parameters which had to be obtained: arrival rate, service rate, carts available, and servers open. Arrival rate and service rate are two of the factors which influence the response variable, waiting time. The arrival rate was initially assumed to be the same for both stores, and then sensitivity analysis was performed varying the arrival rate. The service rate was also initially assumed to be the same for both stores. However, if during the observation of service time, it was found that it was not limited by the bagger operation, we decided we would adjust the service rate to reflect the new cash registers and hold it at that distribution for all simulations. Otherwise, the service rate for the new store was to be the same as for the present store.

The third parameter of interest in our model was the number of servers that are open at any one time. Based upon the observations made at the present commissary, we decided to either keep the number of servers constant for all simulation runs, or vary the number of servers open. Ideally, the commissary attempts to keep all service facilities open during steady-state conditions, but this depends on factors such as leave, sickness, and total number of cashiers available (3). The final parameter needed was the number of carts used per customer. This was needed as an input to the model because in the real system, this is what determines the number of people allowed in the store at any one time. If it was found through observation that the number of customers who had two or more carts was significant, we planned to adjust the model to reflect a more accurate view of the maximum number of people in the store. This was a constant in either case. The present commissary has approximately 152 carts, whereas the new store will have 200 (17). The express line customers rarely use a cart, therefore the maximum number of customers allowed in the checkout system is determined by the maximum number of carts available and the number of customers who use two or more carts.

A final source of data which was used in the validation of our model was the number of transactions per day. These data were being maintained by commissary personnel and were to be compared to the output of the simulation runs to see if the total number of transactions per day were reasonably matched between the simulation and the historical data of the commissary.

Data Collection/Sampling Plan

The four inputs to the model which were acquired through observation at the present commissary were service rate, arrival rate, total number of servers open, and number of customers with two or more carts. One observer monitored the arrival rate and number of carts per customer in one queue, and the other observer monitored the service rate of two cashiers, and the total number of cashiers open. A "customer" was any number of people involved in one transaction. Therefore, if a husband and wife arrived to the queue with one or more carts, they were counted as one customer. The observations took place in half-hour blocks. A random number selection process was used to determine which queue and cashiers/baggers were observed. If one of the two service facilities was closed, the observer monitored the next closest one if possible. The service observer also observed whether or not the bagger kept pace with the cashier.

The major limitation of the data collection was the amount of time that was available for the observations. Due to class schedules and other school requirements, it was not possible to obtain observation data at the commissary for every day of the week or an extremely large number of observations. Hopefully, the observations which were made were spread out sufficiently to reflect an "average/typical" day at the commissary. Because of this limitation, our sample was only considered a convenience sample. Because the population figures may vary from the observed figures, especially for the arrival rate, we used sensitivity analysis in the simulation to account for the possible differences.

Data Analysis and Interpretation

After the data were obtained through observation, they were analyzed prior to their use as input to the simulation model. The service rate and arrival rate were analyzed using either Chi-Square or Kolmogorov-Smirnov goodness of fit tests, which are routines contained in the Statistical Package for the Social Sciences (SPSS) computer program, to determine if the sample (empirical) observations reasonably fit a theoretical distribution. If it was found that the sampled empirical distributions did fit a theoretical probability distribution, for example Poisson, the theoretical distribution was used with the specified parameters.

> The design of a stochastic simulation model always involves a choice of whether to use empirical data directly in the model or to use theoretical probability or frequency distributions. First, using raw empirical data implies that all one is doing is simulating the past. The use of data from one year would replicate only the performance of that year and not necessarily tell us anything about the expected future performance of the system. Second, it is generally more efficient of computer time and storage requirements to use a theoretical frequency or probability distribution rather than to use table look-up procedures for generating the necessary random variates for the model's operation. Third, it is highly desirable, if not almost mandatory, that the analyst determine the sensitivity of his model to the precise form of the probability distribution it contains and the values of the parameters [20:27-28].

After the arrival and service rates were analyzed, the number of carts per customer were analyzed to determine what percentage of observed customers had two or more carts. If necessary, a reduction in the 152/200 maximum customers was then made to the model. The transactions per day figures, which were maintained by the commissary, were used during validation of the model. Once the data was analyzed and interpreted, they were used in the computer model translation.

Model Translation

The computer language that was chosen for this project is Q-GERT. GERT stands for Graphical Evaluation and Review Technique and Q indicates that queueing systems can be modeled graphically (14:vii). "Basically, Q-GERT applications relate to queueing systems analysis or project planning and management [14:5]." Q-GERT was chosen for this simulation for two basic reasons. The first reason was that this language is available on the CREATE computer system used by the AFIT School of Systems and Logistics. The second reason was that Q-GERT is the specialized simulation language that the researchers are familiar with. Because this simulation project specifically dealt with queueing, we believed that Q-GERT was more adequate as the desired computer language.

> Basically, Q-GERT supports a systems approach to problem resolution consisting of four steps. First, a system is decomposed into its significant elements. Second, the elements are analyzed and described. Third, the elements are integrated in a network model of the system. Fourth, system performance is assessed through the evaluation of the network model [14:viii].

The primary criterion of system performance which we were interested in was waiting time in the queue.

The Q-GERT network contains nodes and branches. Within this network, a branch represents an activity that has a processing time or delay. Branches are separated through the use of nodes, and the nodes are used to model milestones, decision points, and queues. The customers for our project are called transactions which flow through the network according to the branching characteristics of the nodes. The activities within the program are used to represent servers of the queueing system, which can be modeled in sequence or in parallel (14:3). Figure 2-1 is a general representation of part of a Q-GERT network. The specific application of Q-GERT will be developed in more detail in Chapter IV.

Once the Q-GERT computer program was developed, it was verified. Verification means to ensure that the model behaves the way the experimenter intends (20:30). This process involved checking the random number generator for proper

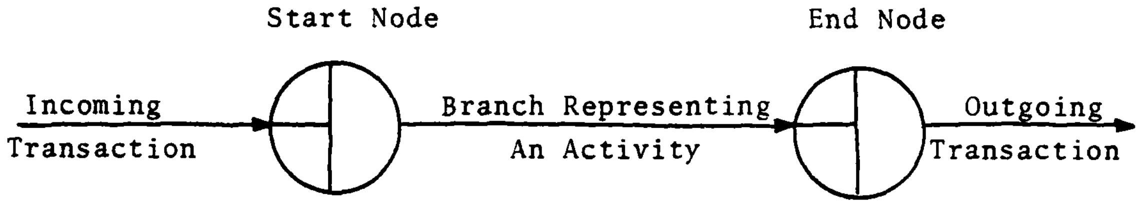


Figure 2-1

Q-GERT Network Example (14:4)

operation, ensuring the mathematical equations were correct, and checking the program for logic errors. After the program was verified, it was ready for input to the computer.

Model Manipulation

The first simulation consisted of modeling the present commissary checkout system. The reason for this was to initially validate the model.

> Validation is the process of bringing to an acceptable level the user's confidence that any inference about a system derived from the simulation is correct. There is no such things as the "test" for validity. Rather, the experimenter must conduct a series of tests throughout the process of developing the model in order to build up his confidence [20:29].

Thus, it can be seen that validation is an ongoing process that is carried on throughout the life of the model. The method of validation used was to compare the behavior of the model with the behavior of the real system. Specifically, the total transactions per day were compared to the historical data to insure that the model was consistent with the real system. Once the initial validation was accomplished, the experimental design aspect of the project was started. This phase can be thought of as strategic planning, or how to design an experiment that will yield the desired information.

> Two types of experimental objectives are readily recognized: (1) finding the combination of parameter values that will optimize the response variable, and/or (2) explaining the relationship between the response variable and the controllable factors in the system. In addition, successful learning requires the full use of prior knowledge in proposing possible hypotheses to be tested or strategies to be evaluated [20:29-30].

Based on our analysis of the new commissary layout, we decided to evaluate four queue configurations: one, two, three, and five lines. We initially decided that the number of servers should be changed to reflect the higher number of cash registers in the new store. The arrival rate was to remain the same as for the present store. The service rate and number of servers open depended upon the observations which were made. As previously stated, if the service rate was not limited by the bagger, it would be adjusted to reflect the new type cash register and remain the same for all simulations. Otherwise, it was to remain the same as for the present store for all simulations. Likewise, the number of servers open was to be set at a constant level or be varied in the simulations.

The next phase is called tactical planning, which is the determination of how each of the test simulation runs was to be executed (20:31). Two primary considerations in this phase were sample size and starting conditions/equilibrium. The sample size refers to the number of simulation runs to be made for a specified set of conditions. Two important factors were important in determining the sample size: computer processing time required and assuring an adequate sample for the statistical analysis. A One-Way ANOVA, comparing average waiting times for the different queue configurations, was selected as the statistical test to be employed. Shannon states, "An experiment on one factor would seldom be considered as adequately replicated unless it had about 8 samples at each level." In addition, he states that the number of degrees of freedom for the error term should be kept at 10 or above (20: 163-164). However, Chou states that for the Central Limit Theorem to be applicable, the number of samples should be 25 or greater (4:243). We decided, therefore, to run each simulation 30 times because it would keep the computer processing time low while more than satisfying the requirements for the One-Way ANOVA test, which will be explained in the analysis section.

The second problem addressed was the selection of starting conditions and the effect of equilibrium/steady-state operations. In this project as in most studies, we were interested in the performance of the system under steady-state conditions as opposed to when the store first opens. Although there are at least three different choices for starting conditions (20:185), we chose to start the simulation with the conditions which we believed most accurately described steady-state operation.

> Our preference, therefore, is to construct a set of starting conditions based upon a compromise of "reasonable" conditions for each of the systems to be compared and then use these compromise conditions for all runs [20:186].

Since each of the alternatives (systems) to be compared consist of only changes in queue configurations, this would not present any problems as long as the reasonable conditions could be ascertained through observation.

The final phase of the actual simulation was sensitivity analysis.

> Sensitivity analysis is one of the most important concepts in simulation modeling. By this, we mean determining the sensitivity of our final answers to the values of the parameters used. Sensitivity analysis usually consists of systematically varying the values of the parameters over some range of interest and observing the effect upon the response of the model. In almost any simulation, many of the set variables are based upon highly questionable data. It is, therefore, extremely important to determine the degree of sensitivity of the results to the values used [20:32].

The sensitivity analysis was performed by varying the arrival rate and assessing the changes in the key response variable, waiting time in the queue.

Model Results and Analysis

After all simulation runs were completed, they were analyzed by comparing the waiting times between different queue configurations for the same arrival rate/service rate. The technique used in the analysis was one-way analysis of variance (ANOVA). For this particular technique, queue configurations were the independent variable or factor. The specific queue configuration (1, 2, 3, or 5) was a factor level or treatment. The response variable was the waiting time. The ANOVA procedure first determines if all the population means are equal. No further analysis is required if they are equal. If they are not equal, the treatment effects are then studied (13:525, 527). The ANOVA model contains three key assumptions: the probability distributions of the response variable are normal, the probability distributions of the response variable have equal variance, and the error terms are independent and normally distributed. By using the Q-GERT random number generator, which internally manipulates the seed values for generation of random variates, independence within each sample was obtained. In addition, since the mean waiting time for each simulation run was actually the mean of n separate means, the first assumption was not a problem as long as the sample size was sufficiently large enough to invoke the Central Limit Theorem, which states: "For almost all populations, the sampling distribution of $\overline{x}$ is approximately normal when the simple random sample size is sufficiently large [13:202]." As stated earlier, our sample size of 30 was large enough to invoke this theorem.

The Cochran C-test was used to ensure that the assumption of equal variances was met (11:62). Even if it was found that this assumption of equal variance was not met in our results, it was still possible to use ANOVA.

> Inferences for model (21.1) involving the F test are not seriously affected by unequal error variances if the sample sizes n_j are equal. However, pairwise comparisons can be seriously affected so that the actual and specified confidence coefficients may differ markedly. Frequently, it is possible to find a mathematical transformation of Y that will produce approximately equal error variance [13:544].

As previously stated, the results of the analysis of variance would reveal whether or not the mean waiting time of the four queue configurations were equal. If they were not equal, we then utilized the Tukey Honestly Significant Differences (HSD) test to determine which means were different through multiple comparison analysis. For the HSD test to perform correctly, the same assumptions required in the ANOVA model were also required (11:88).

Summary

The purpose of this chapter has been to detail the methodology by which we attempted to reduce the waiting time in the Wright-Patterson Commissary. Through the use of simulation, queueing theory was applied. The Q-GERT Analysis Program, a specialized computer simulation language, was used in the modeling of the checkout system, and results of the simulation were analyzed to determine if the waiting time could be reduced by a new queue strategy.

CHAPTER III

DATA COLLECTION AND ANALYSIS

Overview

Data used for this study were collected by observation on five separate days during the period 1 February 1980 to 14 March 1980. The days chosen for observation were selected on a non-interference basis with class schedules and other commitments. During these five days, each researcher observed the present commissary checkout operations for 20 hours, or a total of 40 manhours for the entire project. The observations were conducted so that the checkout operation for each hourly period of the day was observed twice. For example, checkout operation for the 1600-1700 hours time period was observed on 14 February and 13 March. The actual process by which the researchers observed the checkout operations was detailed in Chapter II. During the observations, there were five primary areas in which data were kept: arrival rate, service rate, servers open, carts available, and bagger speed. In addition to these areas, the daily transaction count maintained by the commissary personnel and certain general observations which we made at the commissary also impacted upon this study and will be discussed.

Arrival Rate

A total of 468 arrival observations were made at the commissary checkout queues. The time of arrival was recorded to the second, since in some instances customers arrived to the queue almost simultaneously. The next step was to convert the arrival times into arrivals per five-minute period. This was done so that the arrivals could be analyzed using the SPSS Chi-Square test. It was hypothesized that the observed arrivals per time period were from a Poisson distribution, since many arrival distributions are found to occur in accordance with the Poisson distribution (2:434). There were a total of 219 five-minute time periods. The Chi-Square test was performed on 48 five-minute periods for the 0900-1100 period of operation, and 171 five-minute periods for the 1100-1800 period of operation. The reason for dividing the arrivals into two time periods was due to the observed number of servers open and model limitations. This will be discussed again later in this chapter and in the next chapter.

The results of the Chi-Square test showed that at the .05 level of significance, the arrival distribution for both time periods was Poisson. The mean arrivals per five minutes for the 0900-1100 period was 2.08 arrivals per queue. Since our observations were for only one queue at a time, a system arrival rate was derived by multiplying 2.08 by 4, the number of queues that were open in almost all of our 0900-1100 observations. This yielded a mean of 8.32 arrivals per five minutes to the entire checkout system. This was converted to arrivals per minute by dividing by five and gave us 1.66 arrivals per minute to the system. Since the Q-GERT program cautions against using the Poisson distribution, it was necessary to convert the Poisson distribution to an exponential distribution. The mean of the exponential distribution, which is expressed in time between arrivals, is the inverse of the mean of the Poisson distribution (2:717). Therefore, the Poisson mean of 1.66 was converted to an exponential mean by computing the reciprocal of 1.66, which was .60 minutes between arrivals for the 0900-1100 time period.

The mean arrivals per five minutes per queue for the 1100-1800 time period was 2.17. Since there were usually five queues open during this period, this rate equated to 10.85 arrivals per five minutes to the system, or a mean of 2.17 arrivals per minute to the entire system. This Poisson mean was also converted to an exponential mean and was .46 minutes between arrivals for the 1100-1800 time period.

The .60 and .46 times between arrivals were used as inputs to the validation simulations for the present commissary and the initial simulations for the new commissary. They were also used as the basis for the sensitivity analyses where the arrival rates were varied. In addition to establishing a mean time between arrivals for the exponential distributions used in the computer simulation models, it was necessary to establish the minimum and maximum times between arrivals in order to avoid unrealistic samples generated by the simulations. Therefore, the minimum and maximum times between arrivals for the computer program were based upon observed minimum and maximum times between arrivals.

Service Rate

The service rate or distribution of the service time was based upon 424 service time observations made at the present commissary. It was decided not to break the service time distribution into two time periods similar to the arrival distribution because our observations revealed that the only time period where the service time was significantly different from the rest of the day was from 0800-0900. This is because many of the customers in this time period purchased only a few items which required only a short service time. Therefore, we concluded that the service time should be based upon the 0900-1800 observations. In addition, the 0800-0900 observations revealed that there was not a problem of queues backing up or significant customer waiting time within this time period and often the servers were idle. This was one reason why the simulations were started at 0900 with 12 customers in the queue/queues, which was an average of the observed number of customers in the queues at that time.

The service times for the 0900-1800 observations were analyzed using the Kolmogorov-Smirnov goodness of fit test. We first hypothesized that the times were from a normal distribution and performed the test based upon this assumption. The results at the .05 level of significance showed that the service times were not normally distributed. Based upon this and a closer examination of the data itself, we then hypothesized that the times might be from a lognormal distribution. A lognormal distribution is one where the natural logarithms of the times are normally distributed. We calculated the logarithms of the service times and then tested these for normality, again using the Kolmogorov-Smirnov test. The results of this test showed that the logarithms were normally distributed, therefore the actual service times were lognormally distributed with a mean of 4.46 minutes and a standard deviation of 2.31 minutes. As with the arrival times, the minimum and maximum values specified in the computer programs were based upon the observed minimum and maximum service times.

Servers Open

The researcher who recorded the service times also recorded how many servers were open. These observations were made every five minutes. Based upon the observations, there appeared to be three distinct time periods for the average number of servers open. From 0800-0900, there were 2.75 servers; from 0900-1100, there were 6.04 servers; and from 1100-1800, there was an average of 9.18 servers open. Although we initially tried to model the system with an average number of servers open for the entire day, it was obvious that this did not provide a realistic model. For reasons already stated and the inability to model five queues with only three servers open, the 0800-0900 time period was not modeled. The other two time periods were used due to the natural division in the average number of servers open, model limitations with respect to changing servers, and the limited amount of observation data upon which to statistically determine arrival rates for different time periods.

The average number of servers open for the 0900-1100 time period was rounded up to seven in accordance with practices common to other operations research techniques. For example, in assembly-line balancing, if the computed minimum number of work stations necessary to balance a line for a given cycle time contains a fraction, that fraction is rounded up to the next highest integer value since a fraction of a work station is infeasible (2:632). In a similar manner, the number of servers for the 1100-1800 time period was rounded up to ten servers.

Another observation that impacted upon this study was the fact that at no time during the observations were all 13 regular checkout servers open. This affected the project because even though the new commissary will have 15 regular checkout lanes, it appeared that there were not enough cashiers to utilize all 13 of the present cash registers. This will be addressed again in the next chapter.

Carts Available

The researcher who recorded arrival times also kept track of how many customers had two or more carts, since this affects the maximum number of people allowed in the commissary. Out of 468 arrival observations, it was noted that 53 of these customers had two or three carts. This equated to an average of 11.3 percent of the customers who had two or three carts. Therefore, the maximum number of customers allowed in the present and new commissaries was reduced by 11.3 percent to 135 and 177 respectively. Since the number of customers who had three carts was very small compared to the total of 53 observations, no attempt was made to differentiate between those customers who had two carts and those who had three carts.

Bagger Speed

The final area that was observed was the speed of the bagger in relation to the speed of the checker. Of the 424 service observations, it was found that 66 percent of the time, the bagger either did not have the groceries sacked by the time the checker had returned the receipt and change, or the bagger finished sacking the groceries at the same time the checker completed the transaction. Due to this constraint, we believed that the faster cash registers in the new commissary would not significantly affect the service time. For this reason, the service time distribution for the present commissary was also used in the simulations for the new commissary.

Transactions

The final area of data that was needed for this study was the actual number of transactions per day in the present commissary. Due to a personnel shortage at the commissary during the period of this project, we were only able to obtain the transaction counts for six days of operation in January 1980. The average number of transactions for these six days was 1364 transactions. This number did not include the transactions for express lane 1, but did include the transactions for lane 2 when it was used as an express lane and the 0800-0900 transactions for the entire store. These data were used for the validation phase of the study.

General Observations

During the periods of observation at the commissary, several non-quantitative observations were made that had an impact upon the study. It was observed that when the queue lines were long, some customers got in line and continued to shop while the cart was left in line. We also observed that in some instances the customers did jockey between queue lines, although it was not a significant number when compared to the total number of customers. In fact, on one day the management advised customers to switch lines since there was a wide disparity in the number of customers in the various queues. This is related to the observation which we made that the customers do not always pick the shortest queue line or the queue that has the most servers. Overall, however, the queue lines appeared to be fairly equal with respect to the number of customers in them.

Another observation was that there were consistently slow checkers and consistently fast checkers. The same observation applied to baggers also. This should have been accounted for, however, in the determination of the service time distribution for the total system. It could not be modeled, though, on an individual server basis. Related to this is the possibility of a "Hawthorne effect" due to the observation process (9:292). The checkers and baggers knew they were being observed, and could possibly have speeded up due to this effect. In addition, the checkers and baggers were not briefed by management concerning the purpose of our observations, and this could possibly have affected their performance. There is also a possibility that the checkers and baggers could have varied their speed dependent upon the length of the queue lines. All of these behavioral aspects are important and must be kept in mind, but they could not be accounted for in the data collection or the statistical analyses.

Summary

The primary limitation of the data collection and analyses phase of this project was the limited amount of data which were available for our use. This applied to both the observation data and the data which were maintained by the commissary personnel. We believe, however, that the data which were obtained were more than sufficient for the purpose of this study and reflected the checkout operations at the present commissary.

CHAPTER IV

MODEL FORMULATION AND MANIPULATION

Overview and Model Description

This chapter begins with a description of the Q-GERT network for one of the validation models used in the study and how it functions. This is necessary to fully understand the remaining sections of the chapter. It will be followed by an account of how the models were developed and concluded with a discussion of how the models were manipulated during the sensitivity analysis.

The network being described is the 0900-1100 model which was used for verification and validation (Figure A-1). All subsequent networks for the experiment and the sensitivity analysis are structurally similar to it; the only modifications being the number of queues, the number of servers, and/or the arrival rate. Network diagrams for the 1100-1800 validation model and the 0900-1100 new commissary models are shown in Figures A-2 through A-6. In addition, the computer program listings for these six models are shown in Appendix B.

The network is composed of five queues, one regular, two selector and one statistical nodes, plus five service activities and three regular activities that connect the nodes. Node numbers or labels are contained in the right section of the node while activity numbers are contained in the box below the activity line. The queue nodes are labeled 1, 5, 6, 7, and 8; the regular node is labeled 2; the selector nodes are labeled 3 and 4; and the statistical node is labeled 10. The service activities are labeled 1, 4, 5, 6, and 7, and the regular activities are labeled 2, 3, and 9.

The upper left section of the queue nodes specifies how many transactions are initially in the queue; the lower left section specifies the maximum number of transactions allowed in that queue; and the center section specifies the procedure for ranking transactions within the queue. The upper left sections of the regular and statistical nodes specify the initial number of transactions required to release the node, while the lower left sections of these nodes specify the subsequent number of transactions required to release the nodes. The lower center section of the regular node specifies that a system entry or mark time is assigned to a transaction as it passes through this node. The lower center section of the statistical node specifies what type of statistics will be kept by this node. For example, the I shown in node 10 indicates interval statistics are collected recording the time the transaction resides in the network between node 2 and node 10. The upper center section of both nodes is not required for this model. The upper left section of the selector nodes specifies the queue selection rule to be used while the lower left section is not required for this model.

The specification in parentheses above the service activities assigns a time description to the activity. It contains a function type and a parameter set identifier. The circled number below the activity specifies the number of parallel servers allowed by that service activity. The non-service activities are also labeled, which is optional to the designer.

The network model of the checkout system can be thought of as being divided into separate parts. Nodes 1, 2, 3, and 4 plus activities 1, 2, and 3 simulate a shopper arriving at and selecting a checkout queue. Nodes 5, 6, 7, and 8 simulate the checkout queues where shoppers are waiting to be checked out. Activities 4, 5, 6, and 7 simulate the cashier and bagging operation. Finally, node 10 and activity 9 simulate the shopping cart being given to a new shopper.

The network functions with a transaction waiting in the arrival queue (node 1). Because the ranking procedure is labeled F, transactions are ranked on a First in - First out (FIFO) basis. When a transaction is at the head of the line in the arrival queue and the server in the arrival service activity (activity 1) is idle, the transaction enters the arrival server. The service time for this activity comes from an exponential distribution whose parameters are specified in parameter set 1. This portion of the network simulates customers completing their shopping and arriving at the checkout queue/queues with the time between arrivals in accordance with the specified exponential distribution.

When the transaction is finished being served, it enters node 2 where a mark time is assigned to it as an attribute.

The transaction then departs node 2. Because node 2 is a probabilistic node, there is more than one route it can follow. Activity 2 could route the transaction to node 3 or activity 3 could route it to node 4. Since the transaction can follow only one path, each activity is assigned a probability of the transaction taking that particular path. These probabilities must sum to one. For this network, each activity has a probability of .50. If the transaction is routed to selector node 3, it is assigned a RAN queue selection rule. This means the transaction randomly selects a queue following the selector node. If the transaction is routed to selector node 4, it is assigned a SNQ queue selection rule. This means the transaction will select the queue with the shortest number of transactions in it. The dashed lines from both selector nodes to each of the checkout queues mean that both selector nodes can route their transactions to any of the checkout queues. This portion of the network simulates how the arriving transaction selects which checkout queue to enter.

The four checkout queues form the next portion of the network, simulating four queues are open during this time frame. Each queue has a maximum size based on one-fourth of the total number of carts available minus the transactions being serviced by the cashiers. Each queue receives transactions from either selector node up to its maximum capacity. If a queue becomes full, the transactions are rerouted to other available queues. Again, transactions are ranked on a FIFO basis.

Following the checkout queues are the checkout service activities. Each activity services only the transactions that come from its associated queue. Three of the activities have two servers, or cashier/bagger combinations, while one has only one server. When a server finishes with a transaction, another transaction enters for service. The service time for a transaction comes from a lognormal distribution whose parameters are specified by parameter set two. This portion of the network simulates the cashier/bagger operation.

When a transaction departs a service activity, it enters a statistical node, node 10. Here statistics are calculated on the time interval from the point where the transaction was marked in node 2 until the time it arrived in node 10. By subtracting the average waiting time in the checkout queues, we were able to determine the average service time for the checkout operations, which helped verify this model.

Finally, when a transaction departs the statistical node, it is routed via activity 9 back to the arrival queue. This simulates a cart being returned so a new shopper can utilize it. By modeling the network using this loop, it was possible to limit the system to the number of carts that were available.

This concludes the discussion of how the network functions. Again, each subsequent model is functionally identical to this network. The differences for the various models and the starting conditions for the models will be addressed later in this chapter.

Model Formulation

As stated in Chapter I, the primary objective of this research was to determine if a new queueing system described by one or more different queue configurations could reduce the average customer waiting time in the checkout lines. Four different queue configurations consisting of one, two, three, and five queues were selected for the experimental design. Accordingly, four separate Q-GERT simulation models were designed, one for each queue configuration. The models were very similar in structure with the primary difference being the number of queues and activities required for the different models. Because of this similar structure, if we could validate a model of the present commissary, then the models of the new commissary would also be valid. The specifications for the models of the new commissary are shown in Table C-1. The second character of each program title specifies whether the model is a 0900-1100 model or an 1100-1800 model. For example, N9COMM1 is a 0900-1100 model.

An initial model of the present commissary was formulated with a five-queue line configuration. The number of servers was based on the observed daily average number of cashiers working. The arrival and service rates were also computed as average daily rates. Starting conditions for the model included all transactions in the arrival queue and service activity and zero transactions in the checkout queues and service activities. This replicated the store opening. If this model could be validated, it would have simplified the modeling and analysis tasks by reducing the number of models and statistical tests required, since we were interested in examining only the effects of queue configuration on waiting time. Otherwise, if the number of servers changed over time, then a separate model would be required for each change in server number. This was due to a limitation in the Q-GERT program.

An experimental run of the present commissary model was made to verify that the model and computer program functioned correctly. No errors were detected in the program, and since the result appeared logical, the model was considered to be verified. Next, 30 runs of the model were made for validation. If the average number of transactions for the validation runs was approximately the same as the average number of daily transactions for the actual commissary, then the model would have been considered valid. Because the average number of transactions for the model was approximately 400 less than the average for the commissary, this model was not considered valid.

A reassessment of the data was made and three logical time breaks in the average number of cashiers per hour timeframe was observed. These time frames and related number of servers were as follows:

Time Frame	Average # of Servers
0800-0900	3
0900-1100	7
1100-1800	10

Assessing the arrival and service rate data, we concluded, as stated in Chapter III, that the arrival rates for time-frames should be separated, resulting in a specific arrival rate for each time-frame. In addition, we concluded that one service rate would be applicable to all time-frames. Furthermore, we concluded that the 0800-0900 time-frame could be deleted from the study without affecting the results. This conclusion was based upon personal observation that there appeared to be no real problem of waiting time in the queues for the 0800-0900 time-frame and the inability to include a five-queue model in the analysis because an average of only three servers were utilized.

A second model was constructed of the present commissary for verification and validation purposes. This actually required two separate models, a 0900-1100 model and an 1100-1800 model, in order to allow for increasing the number of servers from one time period to the next. The Q-GERT program does allow for changing the number of queues and servers through nodal modification, thus allowing use of a single model, however, the current number of transactions in the queues at these changes are lost. By creating two separate models, we were not able to input the exact number of transactions remaining from the 0900-1100 model into the 1100-1800 model, but we were able to input an average number remaining which we felt would be more meaningful than had we used observed data, especially when the sensitivity analysis runs were made.

Since the verification and validation model now consisted of two separate programs beginning at 0900 and 1100, respectively, new starting conditions were required. For the 0900 model, we averaged the total number of people waiting in checkout queues at 0900 from the observed data and computed 12 transactions. As there were four checkout queues, that meant three transactions were initially in each queue. Since three customers were in each queue, each checkout server was busy. To arrive at the initial number of transactions in the arrival queue, the total number of transactions in the checkout queues, checkout servers, and the transaction in the arrival service activity were subtracted from the total number of carts available. This same process was used to compute starting conditions for all subsequent 0900 models.

Starting conditions for the 1100 model of the present commissary were computed somewhat differently. The average current number of transactions for each queue at the end of the two-hour simulation was computed from all individual 0900 model runs. Three queues contained eight transactions and one contained nine. A fifth queue was created at 1100 and its initial number was zero, simulating its startup. The initial number of transactions in the arrival queue was calculated using the same method for the 0900 model. Computations of starting conditions for all subsequent 1100 models were made in the same manner, using each model's respective 0900 model current queue number.

Another characteristic of the 0900 and 1100 models was the queue selection process. Initially, a single selector node with the RAN selection rule was utilized. This meant that each arrival transaction randomly selected a queue to enter. Since modeling individual behavior is difficult, we felt that this would best model the queue selection mode.

When the 0900 and 1100 models of the present commissary were run for verification and validation, problems were again encountered. These models both functioned correctly and the total number of transactions was approximately the same as the actual number of transactions per day in the commissary. But the number of transactions within the queues varied considerably. One queue might have no or relatively few transactions waiting while another queue, at the same time, might have the maximum number of transactions allowed. For this reason, these models were not considered valid.

To alleviate this problem, each model was modified. Two queue selector nodes were included: one with the RAN selection rule and one with the SNQ selection rule. The SNQ selection rule meant that the arriving transaction selected the checkout queue with the fewest number of transactions waiting. A .50 probability was assigned to each of the selector nodes. The models were again run for verification and validation. The results indicated that the models functioned correctly; the total number of transactions was approximately the same as in the actual commissary, and the number of transactions within each queue were approximately equal. We, therefore, concluded that the models were valid.

The next step was to construct the models for the new commissary which were used in the research design. The models for the new commissary covered the same time-frames and were structurally identical to the models of the present commissary, with the exception of the number of queues. Starting conditions for each model were computed using the same method as previously described. The number of checkout servers for the new commissary experimental models was also identical to that of the present commissary. This was because commissary management personnel had stated that at the present time, it was not anticipated any additional cashiers would be hired for the new commissary (3). As stated in Chapter II, each model simulation consisted of 30 runs so that average waiting times for each run could be input into the ANOVA statistical test for analysis.

Model Manipulation

Initially, the sensitivity analysis was to be conducted by varying the arrival rate and keeping the number of servers equal to the experimental models. One set of simulations would increase the number of arrivals by 25 percent and the other set would decrease the number of arrivals by 25 percent. The Q-GERT analysis program utilizes time between arrivals as the arrival rate instead of number of arrivals per time period. A percentage change in number of arrivals does not equal the same percentage change in arrival rates. Therefore, the percentage increases and decreases in arrival rates were calculated initially in numbers of arrivals and then converted to arrival rate so as to remain consistent with commissary management forecasts. These increased and decreased arrival rates were designed to account for any errors in the arrival rates we computed from our limited observations. In addition, the increased arrival rate accounted for the increased business the new commissary is expected to have.

Because the sensitivity analysis models only changed arrival rates, the models were structurally identical to the experimental new commissary models. Starting conditions for the 0900 sensitivity analysis models were also identical. Starting conditions for the 1100 sensitivity analysis models were different though because they had to be calculated from the current number in the queue output of the 0900 sensitivity analysis models. Again, each simulation model was run 30 times for input to the ANOVA statistical test.

Before conducting the ANOVA tests, the results from the two sensitivity analyses were examined. As expected, the model where the arrival rate was decreased indicated very short waiting times in the checkout queues, and at times some checkout servers were idle. This occurred once during one observation; however, commissary personnel stated that it is a very rare occurrence (3).

When the results of the model with the increased arrival rate were examined, it was found that in most cases, the queues were exploding. This means that the servers cannot keep up with the people arriving to the checkout queues and the number of people in the queues is increasing at such a rate that eventually most of the people will be in the checkout queues or server activities and very few will be shopping.

Because this is totally unrealistic, two more sensitivity analysis models were built. One increased the number of arrivals by 10 percent and kept the number of servers equal to the experimental model. The second increased the number of arrivals by 25 percent and, in addition, increased the number of checkout servers by 25 percent.

When the model with a 10 percent increase in arrivals was examined, there was some evidence of exploding queues; however, this was the exception and not the general case. When the model where the number of arrivals and number of servers was increased by 25 percent, there was no indication of of queue explosion.

Summary

This concluded the model formulation and manipulation for the study. Chapter V will present the results and analysis of the models. It will also include the conclusion of the study and recommendations.

CHAPTER V

RESULTS, CONCLUSIONS AND RECOMMENDATIONS

Overview and Analysis Methodology

This chapter includes a description of how the output from the experimental and sensitivity analysis models was analyzed followed by a brief summary of the results for each of the models. Following this there will be a discussion of the conclusions reached by the researchers. This chapter concludes with recommendations based upon the results of the study and other recommendations based upon observations by the researchers during the course of the study.

As stated in Chapter IV, there were many separate models and programs required during the course of this study. A total of 42 networks and computer programs were formulated and executed during the validation, experimentation, and sensitivity analysis portions of the study. Table C-1 contains a listing of the various programs and the number of queues, number of servers, and mean time between arrivals for each. The 0900 and 1100 networks for each of the various models are grouped together and the models are arranged in the order in which they were formulated and executed.

The first task in the analysis was to determine the average waiting times for each of the models since this was the response variable to be used for the study. The Q-GERT analysis programs list the number of transactions and the average waiting times for each queue for each run and provide a summary average waiting time for each queue for all runs associated with the execution of each model. Because we were interested in examining the average waiting time per customer, and since the number of transactions varied between queues within runs and between runs, neither a simple average of the summary nor individual run averages was adequate for the analysis. We believed that a weighted average waiting time was necessary to provide an average waiting time per customer for each model. To compute the weighted average for each model, a weighted average time for each individual run was calculated by weighting each queue average by the number of transactions passing through it. These individual run, weighted average waiting times were the inputs for the ANOVA tests.

As stated in Chapter II, one-way analysis of variance (ANOVA) was to be the statistical test utilized to determine if there were any differences between waiting times for the different queue configurations. For ANOVA to be applicable, three assumptions were required to be met: the probability distributions of the response variables were normal, the probability distributions of the response variables had equal variances, and the error terms were independent and normally distributed. Shannon states, "If each sample is itself a mean . . . , then the central limit theorem holds and we can assume normality of the response [20:187]." Additionally, Chou states that the sample size must be 25 or greater (4: 243). Because the sample sizes for the simulations were 30 and each sample was itself a mean, the requirements for the first assumption were met.

Cochran's C-test for homogeneity of variance was utilized to assure that the second assumption for ANOVA was met (11:62). Appendix C contains an example of Cochran's C-test, including the hypotheses, the calculations, and the decision rule. Included in Table C-2 are the variances and Cochran's $C_{calculated}$ values for all simulations. For all C-tests, the $C_{critical}$ test statistic was the same. Since in each test, C_{cal} was less than C_{crit}, the variances for each of the ANOVA comparisons were found to be equal.

The third assumption required for ANOVA was that the error terms be independent and normally distributed. By using the Q-GERT random number generator, which internally manipulates the seed values for generation of random variates, independence within each sample was obtained. Invoking the central limit theorem, because the sample sizes were greater than 25 and each sample itself was a mean, assured each error term was normally distributed. Therefore, the third and final assumption for ANOVA was met.

The ANOVA tests were conducted utilizing the ANVA5 computer program, available on the CREATE computer system used by the AFIT School of Systems and Logistics. An example of the ANOVA analysis is contained in Appendix C, including the ANVA5 output, hypotheses calculations, and decision rule.

Also included in Table C-2 are the $F_{calculated}$ values for each of the ANOVA tests. For all comparisons, the $F_{critical}$ test statistic was the same. The specific results for each of the ANOVA tests will be addressed in the results section of this chapter.

Upon completion of the ANOVA tests, if the average waiting times were statistically equal, then no further analysis was required. However, if not all the average waiting times were equal, then Tukey's Honestly Significant Difference (HSD) test was utilized to determine which means were different (11:62). The same assumptions were required for Tukey's HSD test as were required for the ANOVA tests and were similarly met. An example of Tukey's HSD test is listed in Appendix C, which includes the calculations, decision rule, and results. Those ANOVA tests that required further analysis and the Tukey's HSD test results for each will be addressed in the results section of this chapter.

Results

The results of the analysis of each set of simulations are shown in Table C-2. These tables display the results of the Cochran C-test, the analysis of variance, and the Tukey HSD test if applicable. The results of each set of simulations will now be briefly discussed.

Simulations N9COMM and N11COMM. These sets of simulations were the experimental design models which utilized the observed arrival rates and observed number of servers open.

The ANOVA test results showed that the average waiting times were equal for the four queue configurations within each set of simulations.

Simulations S9COMM and S11COMM. These simulations were the first of the sensitivity analysis models which we accomplished. The only change from the experimental design simulations was increased arrival rates for each simulation set based upon the forecast of a 25 percent increase in sales/customers. As with the experimental design simulations, the ANOVA test revealed there was no difference between any of the average waiting times for either set of simulations.

Simulations R9COMM and R11COMM. In contrast to the previous simulations which had an increased arrival rate, these sets of sensitivity analysis simulations were performed with decreased arrival rates based upon a 25 percent reduction in sales/customers. This was done in order to account for the possibility that our observed arrival rates may have been too high due to the limited number of observations. The ANOVA test of the R9COMM simulations showed that not all average waiting times were equal. The Tukey test was then performed and showed that the waiting time for the one queue configuration was statistically less than the waiting time for the five queue configuration. However, all other queue configurations were found to be equal when compared to one another. In contrast, the ANOVA and Tukey tests for the R11COMM simulations indicated that all of the average waiting times were unequal.

Simulations S9C and S11C. Based upon the results of simulations S9COMM and S11COMM, where the queues were approaching the point of explosion, we decided to increase the number of servers by 25 percent for these simulations in addition to the increased arrival rate. The increased number of servers reduced the waiting time significantly over the S9COMM and S11COMM simulations. However, the ANOVA results showed that the average waiting times were statistically equal for the various queue configurations for both sets of simulations.

Simulations A9COMM and A11COMM. These sets of sensitivity analysis simulations were also based upon the results of the S9COMM and S11COMM simulations. The number of servers was kept at the same level of those simulations, but the arrival rate was based upon only a 10 percent increase in customers as opposed to a 25 percent increase. The ANOVA test and subsequent Tukey test showed that the average waiting time for one queue was statistically less than that of two queues for A9COMM. All other average waiting times were found to be equal. The ANOVA test for the A11COMM simulations revealed that all of the average waiting times were equal.

Conclusions and Recommendations

Based upon the analysis, there were three conditions studied where the average waiting time per customer was reduced because of queue configuration. Therefore, we failed to reject the null hypothesis that a new checkout queue system will significantly reduce the average customer waiting time. We do realize that under the other conditions studied, the average waiting time remains unchanged.

In each of the instances where average waiting time was reduced, the only queue configuration to consistently reduce the average waiting time was the single queue configuration. Therefore, the answer to our research question is that under certain conditions, a single queue configuration will reduce the average customer waiting time. Again, we realize that under the other conditions studied, the average waiting time remains unchanged.

Based upon these conclusions, the researchers recommend that the management of the Wright-Patterson Commissary implement a single queue configuration for checkout operations when the new commissary is opened. This is because when conditions prevail where a single queue configuration will reduce waiting time, customers will have a shorter average waiting time. Additionally, when conditions prevail where the waiting time is unchanged, there would be no difference in waiting time, regardless of which queue configuration was in effect.

There are two additional advantages to implementing a single queue configuration. First, a single queue configuration will provide equity between customer waiting times. For example, customers will not be penalized because the queue which they entered is slower, for reasons such as slow checkers or a register was closed after the customer entered the line. Secondly, when slack business conditions exist, management will not have to monitor the queues to insure that a checker does not become idle while a customer is waiting in another line.

As discussed in Chapter I, there is a possible disadvantage to implementing a single queue configuration. That is, a customer may perceive he would have to spend more time in one longer line than in one of several shorter lines. We believe that customer education by the commissary would resolve this problem.

In addition to the recommendation for implementing a single queue configuration, we suggest several other recommendations. The first recommendation is that another study should be conducted that would further this research. This study should include more observation data in order to increase the validity of the parameters used in the model of the checkout system.

The second recommendations is that commissary management consider implementing three-man bagger teams, as opposed to the current two-man teams. This would probably reduce the bagging time, which would allow the commissary to take advantage of the faster NCR 255 cash registers to be installed in the new facility. Although the baggers may oppose this because they feel a three-way split of tips will decrease their wages, the increase in the number of customers processed could have offsetting effects.

Another recommendation is that a better cashier scheduling system should be considered. During the course of our observations, we noted that in some instances there were either too few cashiers or too many cashiers with which to accommodate the number of customers. A new scheduling system could possibly alleviate some of the waiting time problems under present conditions without the addition of new cashier personnel. However, if the forecasted increase in business does occur, a new scheduling system for the current labor force may not alleviate the problem of long customer waiting times.

This leads to our final recommendation, which is that management should consider hiring more cashiers to accommodate the forecasted increase in business at the new commissary. This recommendation is based upon the two sensitivity analysis simulations where the arrival rates were increased and servers remained at the current level. In both cases, the queues approached the point of explosion. Therefore, we believe more cashiers will be needed in the new commissary. This, combined with a better scheduling system and the implementation of a single queue configuration, should lead to the largest reduction in customer waiting time.

APPENDIX A

Q-GERT NETWORKS

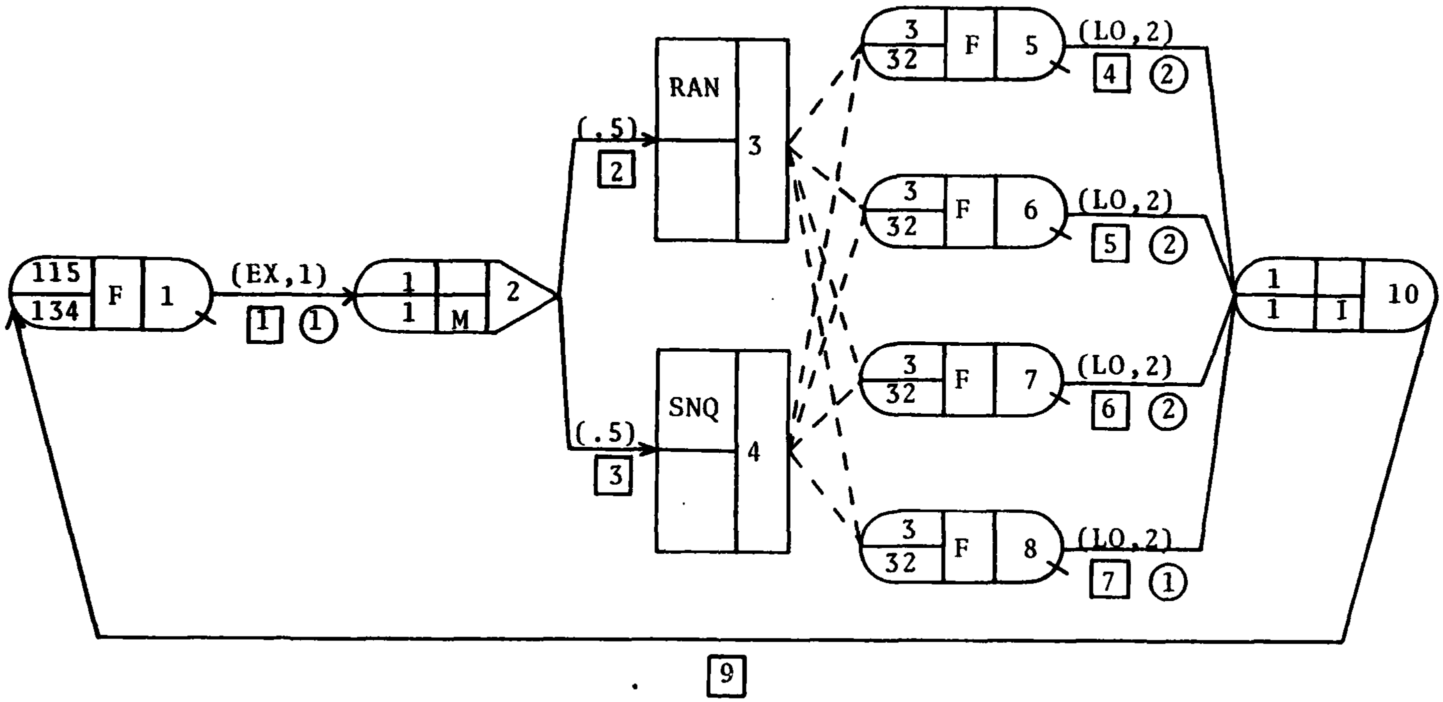


Figure A-1

OLDCOMM7

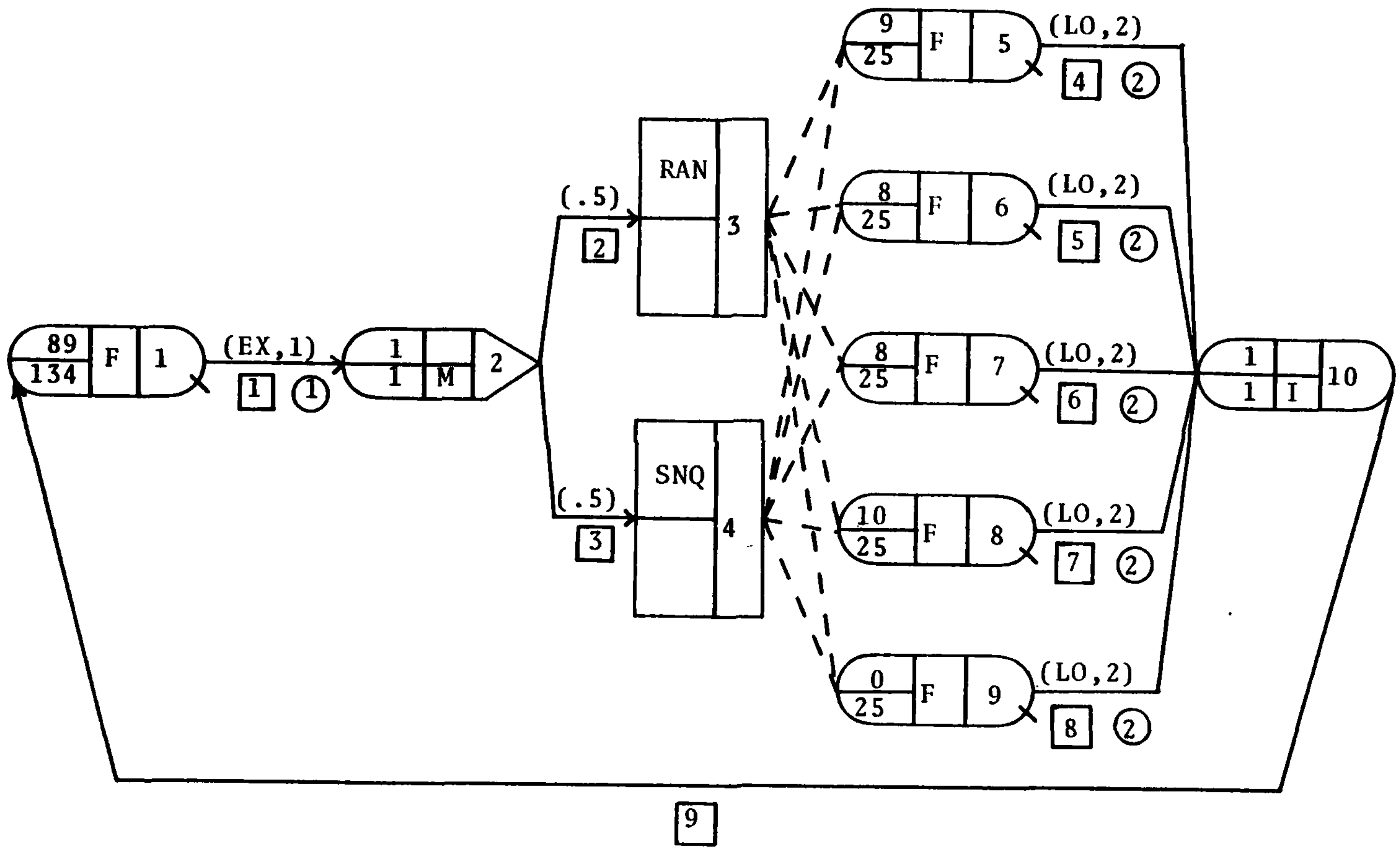


Figure A-2

OLDCOMM10

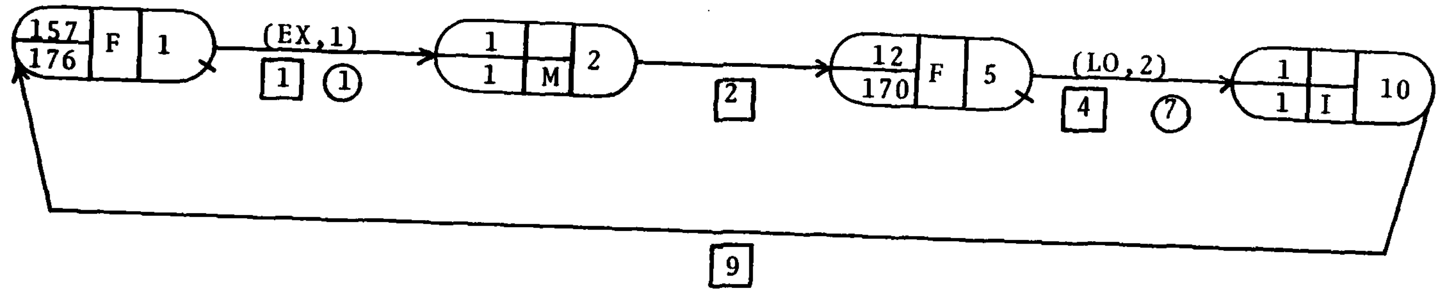


Figure A-3

N9COMM1

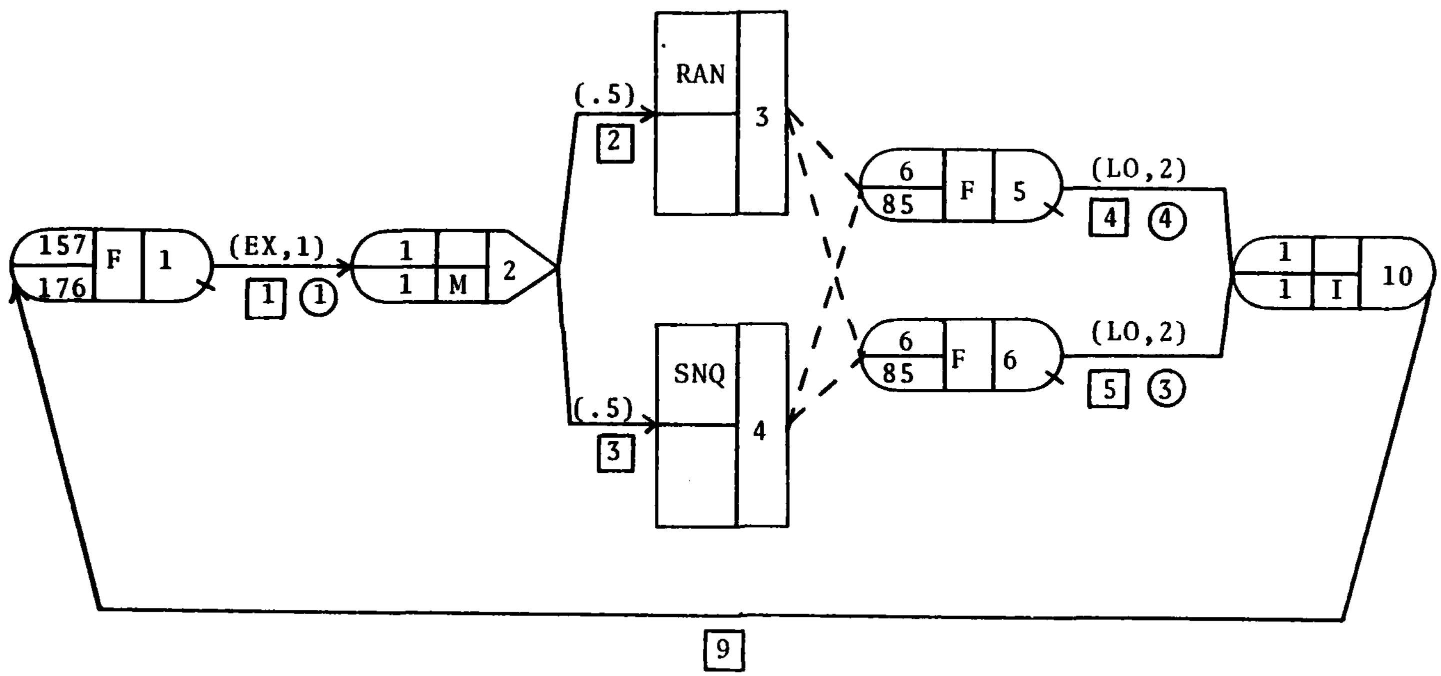


Figure A-4

N9COMM2

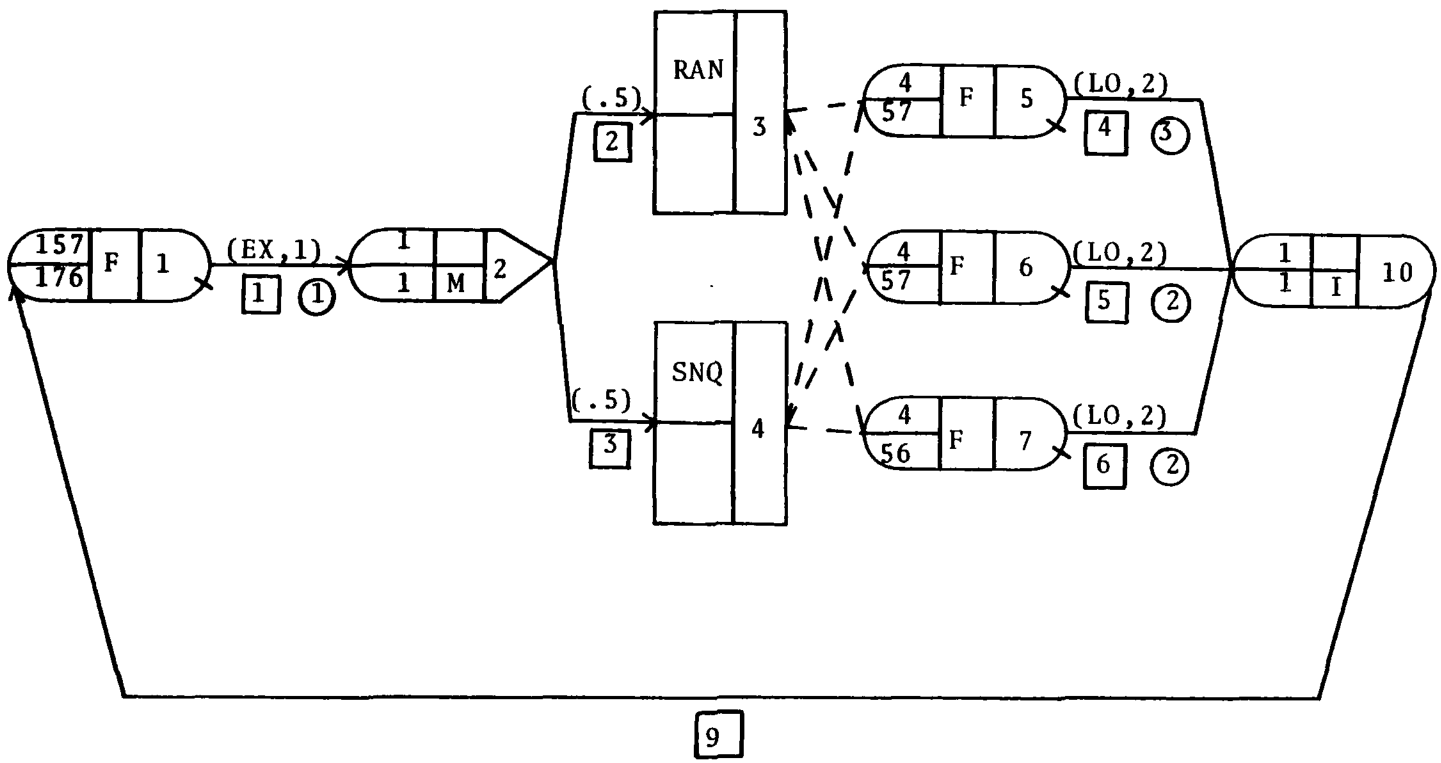


Figure A-5

N9COMM3

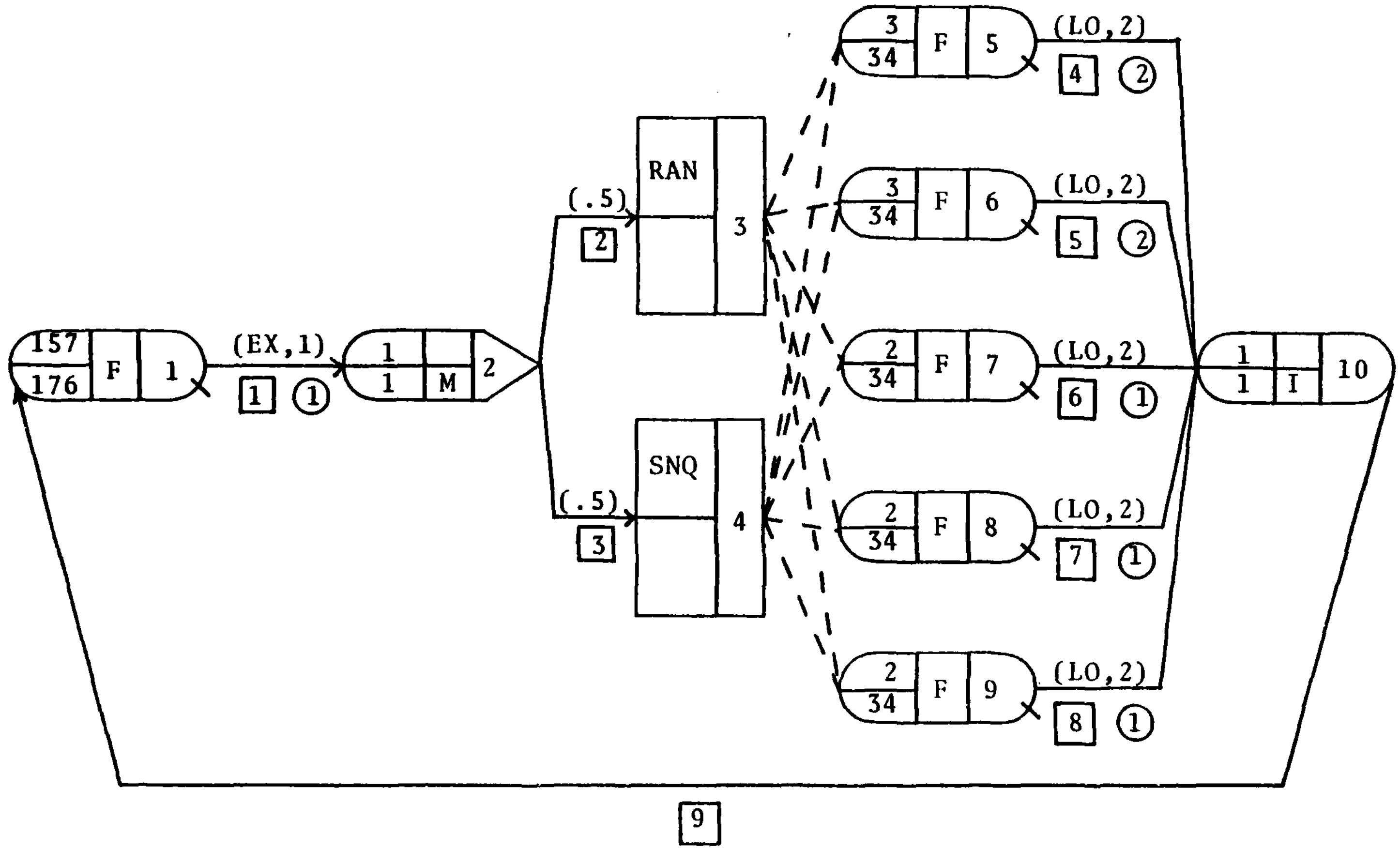


Figure A-6

N9COMM5

APPENDIX B

Q-GERT SIMULATION PROGRAM LISTINGS

Computer Listing - OLDCOMM7

```
GEN,ROB&BOB,OLDCOMM7,4,11,1980,1,0, ,120.,30,E*
QUE,1/ARRIVEQ,115,134*
ACT,1,2,EX,1,1/ARRIRATE*
REG,2,1,1,P,M*
ACT,2,3, , ,2/RANSELQ*
ACT,2,4, , ,3/SNQSELQ*
SEL,3/RAN,RAN,(7)5,6,7,8*
SEL,4/SNQ,SNQ,(7)5,6,7,8*
QUE,5/QUE2,3,32*
QUE,6/QUE3,3,32*
QUE,7/QUE4,3,32*
QUE,8/QUE5,3,32*
ACT,5,10,LO,2,4/SERVQ2,2*
ACT,6,10,LO,2,5/SERVQ3,2*
ACT,7,10,LO,2,6/SERVQ4,2*
ACT,8,10,LO,2,7/SERVQ5,1*
STA,10/SYSTIME,1,1,D,I*
ACT,10,1, , ,9/RETCART*
PAR,1,.6,.02,2.25*
PAR,2,4.46,.40,16.2,2.31*
FIN*
```

Computer Listing - OLDCOMM10

```
GEN,ROB&BOB,OLDCOM10,4,11,1980,1,0, ,420.,30,E*
QUE,1/ARRIVEQ,89,134*
ACT,1,2,EX,1,1/ARRIRATE*
REC,2,1,1,P,M*
ACT,2,3, , ,2/RANSELQ*
ACT,2,4, , ,3/SNQSELQ*
SEL,3/RAN,RAN,(7)5,6,7,8,9*
SEL,4/SNQ,SNQ,(7)5,6,7,8,9*
QUE,5/QUE2,9,25*
QUE,6/QUE3,8,25*
QUE,7/QUE4,8,25*
QUE,8/QUE5,10,25*
QUE,9/QUE6,0,25*
ACT,5,10,LO,2,4/SERVQ2,2*
ACT,6,10,LO,2,5/SERVQ3,2*
ACT,7,10,LO,2,6/SERVQ4,2*
ACT,8,10,LO,2,7/SERVQ5,2*
ACT,9,10,LO,2,8/SERVQ6,2*
STA,10/SYSTIME,1,1,D,I*
ACT,10,1, , ,9/RETCART*
PAR,1,.46,.02,2.4*
PAR,2,4.46,.40,16.2,2.31*
FIN*
```

Computer Listing - N9COMM1

```
GEN,ROB&BOB,N9COMM1,4,11,1980,1,0,,120.,30,E*
QUE,1/ARRIVEQ,157,176*
ACT,1,2,EX,1,1/ARRIRATE*
REG,2,1,1,D,M*
ACT,2,5,,,2*
QUE,5/QUE1,12,170*
ACT,5,10,LO,2,4/SERVQ1,7*
STA,10/SYSTIME,1,1,D,I*
ACT,10,1,,,9/RETCART*
PAR,1,.6,.02,2.25*
PAR,2,4.46,.40,16.2,2.31*
FIN*
```

Computer Listing - N9COMM2

```
010 GEN,ROB&BOB,N9COMM2,4,11,1980,1,0,0,120.,30,E*
020 QUE,1/ARRIVEQ,157,176*
030 ACT,1,2,EX,1,1/ARRIRATE*
040 REG,2,1,1,P,M*
050 ACT,2,3,,,2/RANSELQ*
060 ACT,2,4,,,3/SNQSELQ*
070 SEL,3/RAN,RAN,(7)5,6*
080 SEL,4/SNQ,SNQ,(7)5,6*
090 QUE,5/QUE2,6,85*
100 QUE,6/QUE3,6,85*
110 ACT,5,10,LO,2,4/SERVQ2,4*
120 ACT,6,10,LO,2,5/SERVQ3,3*
130 STA,10/SYSTIME,1,1,D,I*
140 ACT,10,1,,,9/RETCART*
150 PAR,1,.6,.02,2.25*
160 PAR,2,4.46,.40,16.2,2.31*
170 FIN*
```

Computer Listing - N9COMM3

```
010 GEN,ROB&BOB,N9COMM3,4,11,1980,1,0, ,120.,30,E*
020 QUE,1/ARRIVEQ,157,176*
030 ACT,1,2,EX,1,1/ARRIRATE*
040 REG,2,1,1,P,M*
050 ACT,2,3, , ,2/RANSELQ*
060 ACT,2,4, , ,3/SNQSELQ*
070 SEL,3/RAN,RAN,(7)5,6,7*
080 SEL,4/SNQ,SNQ,(7)5,6,7*
090 QUE,5/QUE2,4,57*
100 QUE,6/QUE3,4,57*
110 QUE,7/QUE4,4,56*
120 ACT,5,10,LO,2,4/SERVQ2,3*
130 ACT,6,10,LO,2,5/SERVQ3,2*
140 ACT,7,10,LO,2,6/SERVQ4,2*
150 STA,10/SYSTIME,1,1,D,I*
160 ACT,10,1, , ,9/RETCART*
170 PAR,1,.6,.02,2.25*
180 PAR,2,4.46,.40,16.2,2.31*
190 FIN*
```

Computer Listing - N9COMM5

```
010 GEN,ROB&BOB,N9COMM5,4,11,1980,1,0,,120.,30,E*
020 QUE,1/ARRIVEQ,157,176*
030 ACT,1,2,EX,1.1/ARRIRATE*
040 REG,2,1,1,P,M*
050 ACT,2,3,,,2/RANSELQ*
060 ACT,2,4,,,3/SNQSELQ*
070 SEL,3/RAN,RAN,(7)5,6,7,8,9*
080 SEL,4/SNQ,SNQ,(7)5,6,7,8,9*
090 QUE,5/QUE2,3,34*
100 QUE,6/QUE3,3,34*
110 QUE,7/QUE4,2,34*
120 QUE,8/QUE5,2,34*
130 QUE,9/QUE6,2,34*
140 ACT,5,10,LO,2,4/SERVQ2,2*
150 ACT,6,10,LO,2,5/SERVQ3,2*
160 ACT,7.10,LO,2,6/SERVQ4,1*
170 ACT.8,10,LO,2,7/SERVQ5,1*
180 ACT,9,10,LO,2,8/SERVQ6,1*
190 STA,10/SYSTIME,1,1,D,I*
195 ACT,10,1,,,9/RETCART*
200 PAR,1,.6,.02,2.25*
210 PAR,2,4.46,.40,16.2,2.31*
220 FIN*
```

APPENDIX C

MODEL SPECIFICATIONS, ANALYSIS, AND RESULTS

TABLE C-1

Simulation Program Specifications

Program	# Queues	# Servers	Mean Time Between Arrivals
N9COMM1	1	7	.60
N9COMM2	2	7	.60
N9COMM3	3	7	.60
N9COMM5	5	7	.60
N11COMM1	1	10	.46
N11COMM2	2	10	.46
N11COMM3	3	10	.46
N11COMM5	5	10	.46
S9COMM1	1	7	.48
S9COMM2	2	7	.48
S9COMM3	3	7	.48
S9COMM5	5	7	.48
S11COMM1	1	10	.368
S11COMM2	2	10	.368
S11COMM3	3	10	.368
S11COMM5	5	10	.368

TABLE C-1 continued

Program	# Queues	# Servers	Mean Time Between Arrivals
R9COMM1	1	7	.80
R9COMM2	2	7	.80
R9COMM3	3	7	.80
R9COMM5	5	7	.80
R11COMM1	1	10	.613
R11COMM2	2	10	.613
R11COMM3	3	10	.613
R11COMM5	5	10	.613
S9C1	1	9	.48
S9C2	2	9	.48
S9C3	3	9	.48
S9C5	5	9	.48
S11C1	1	13	.368
S11C2	2	13	.368
S11C3	3	13	.368
S11C5	5	13	.368

TABLE C-1 continued

Program	# Queues	# Servers	Mean Time Between Arrivals
A9COMM1	1	7	.545
A9COMM2	2	7	.545
A9COMM3	3	7	.545
A9COMM5	5	7	.545
A11COMM1	1	10	.418
A11COMM2	2	10	.418
A11COMM3	3	10	.418
A11COMM5	5	10	.418

Cochran's C-test

Program - A9COMM

	A9COMM1	A9COMM2	A9COMM3	A9COMM4
$\bar{X}$	14.037	17.005	15.547	16.255
σ^2	14.048	13.965	14.692	9.530

Hypothesis:

H_0: All variances are equal

H_1: Not all variances are equal

$$C_{cal} = \frac{\sigma_j^2 \text{ largest}}{\sum_{j=1}^{k} \sigma_j^2} = \frac{14.692}{52.235} = .281$$

$$C_{crit} = C(\alpha;\ k,\ n-1) = C(.05;\ 3,\ 116) = .3914$$

Decision Rule:

If $C_{cal} \leq C_{crit}$, fail to reject H_o

If $C_{cal} > C_{crit}$, reject H_o

Since C_{cal} (.281) < C_{crit} (.3914), fail to reject H_o

ANOVA Results

Program - A9COMM

Source	Sum of Squares	Degrees of Freedom	Mean Square
A(Between)	143.9928	3	47.99759
SSE	1567.041	116	13.50897
SST	1711.034	119	14.37843

Hypotheses:

H_0: All average waiting times are equal

H_1: Not all average waiting times are equal

$$F_{cal} = \frac{MSB}{MSE} = \frac{47.99759}{13.50897} = 3.553$$

$$F_{crit} = F(\alpha;\ k-1,\ N-k) = F(.05;\ 3,\ 116) = 2.68$$

Decision Rule:

If $F_{cal} \leq F_{crit}$, fail to reject H_0

If $F_{cal} > F_{crit}$, reject H_0

Since F_{cal} (3.553) > F_{crit} (2.68), reject H_0

Tukey HSD Test Results

Program - A9COMM

$\bar{X}$	A9COMM1	A9COMM3	A9COMM5	A9COMM2
A9COMM1 (14.037)	---	1.51	2.218	2.968*
A9COMM3 (15.547)	---	---	.708	1.458
A9COMM5 (16.255)	---	---	---	.75
A9COMM2 (17.005)	---	---	---	---

Array value = higher $\bar{X}$ - lower $\bar{X}$

*Statistical difference between means

$$HSD = q(\alpha;\ r,\ N\text{-}k)\sqrt{\frac{MSE}{n}}$$

$$= q\ (.05;\ 4,\ 116)\sqrt{\frac{13.509}{30}} = (3.68)(.671)$$

$$= 2.469$$

Decision Rule:

If the array value is greater than HSD, there is a statistical difference between the mean values.

The array value of 2.968 for comparison A9COMM1/A9COMM2 is greater than the HSD of 2.469. Therefore, there is a statistical difference between the average waiting times of simulations A9COMM1 and A9COMM2

TABLE C-2

Simulation Results

Program	Avg. Wait Time	Variance	F_{cal}	C_{cal}	ANOVA Result	Tukey Result
N9COMM1	12.421	15.218	1.179	.347	All Equal	N/A
N9COMM2	12.348	23.824				
N9COMM3	13.080	20.621				
N9COMM5	11.082	8.934				
N11COMM1	9.877	32.661	.660	.325	All Equal	N/A
N11COMM2	11.083	25.847				
N11COMM3	11.581	19.483				
N11COMM5	10.360	22.382				
S9COMM1	21.219	10.491	.267	.362	All Equal	N/A
S9COMM2	20.761	11.916				
S9COMM3	21.159	17.615				
S9COMM5	20.515	8.667				
S11COMM1	55.651	9.697	.481	.348	All Equal	N/A
S11COMM2	55.870	5.837				
S11COMM3	55.176	4.558				
S11COMM5	55.208	7.806				

TABLE C-2 continued

Program	Avg. Wait Time	Variance	F_{cal}	C_{cal}	ANOVA Result	Tukey Result
R9COMM1	3.47	1.852	3.189	.381	Not All Equal	R9COMM1 and R9COMM5 Unequal
R9COMM2	4.024	4.121				
R9COMM3	4.448	2.893				
R9COMM5	4.947	5.448				
R11COMM1	.308	.018	92.087	.319	Not All Equal	All Unequal
R11COMM2	.476	.024				
R11COMM3	.658	.035				
R11COMM5	1.008	.036				
S9C1	9.761	10.157	.675	.304	All Equal	N/A
S9C2	9.443	15.674				
S9C3	8.996	16.524				
S9C5	10.334	12.083				
S11C1	5.316	6.131	2.022	.342	All Equal	N/A
S11C2	5.111	11.069				
S11C3	4.568	6.875				
S11C4	6.466	12.525				

TABLE C-2 continued

Program	Avg. Wait Time	Variance	F_{cal}	C_{cal}	ANOVA Results	Tukey Results
A9COMM1	14.037	14.048	3.553	.281	Not All Equal	A9COMM1 and A9COMM2 Unequal
A9COMM2	17.005	13.965				
A9COMM3	15.547	14.692				
A9COMM5	16.255	9.530				
A11COMM1	32.199	46.458	2.165	.296	All Equal	N/A
A11COMM2	36.310	40.615				
A11COMM3	33.804	34.669				
A11COMM5	33.573	35.307				

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